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Micro- and Nanoscale Mechanical Testing

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

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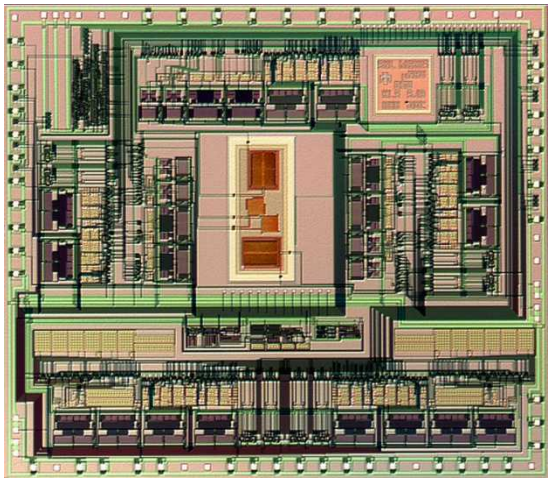
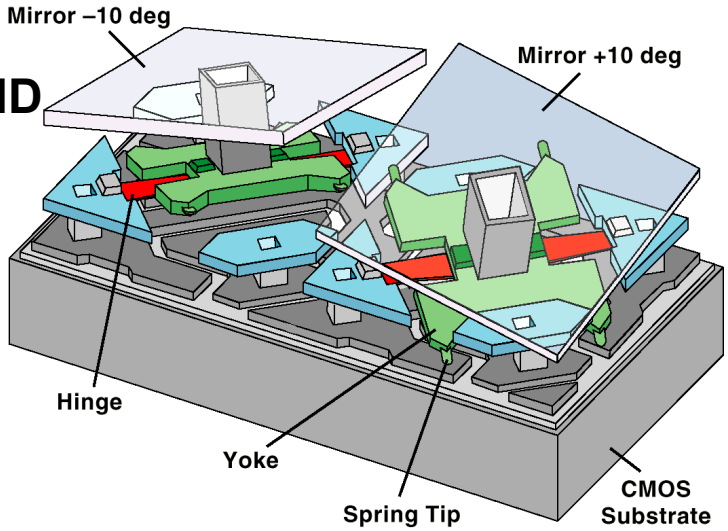
With MEMS we can accomplish electromechanical and optical functions

-thousands of devices simultaneously
-no assembly required
-hundreds of device concepts explored

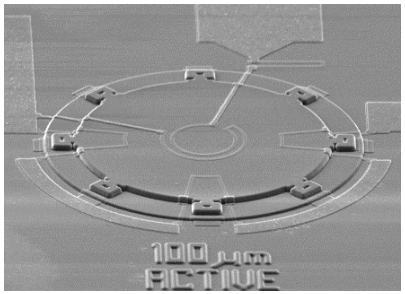
Integrated inertial sensor



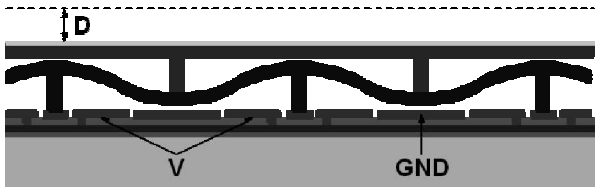
TI DMD



Pressure sensor



Polychromator : programmable diffraction grating



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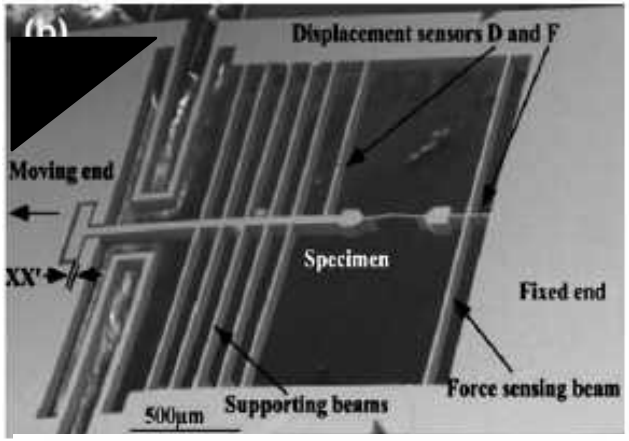
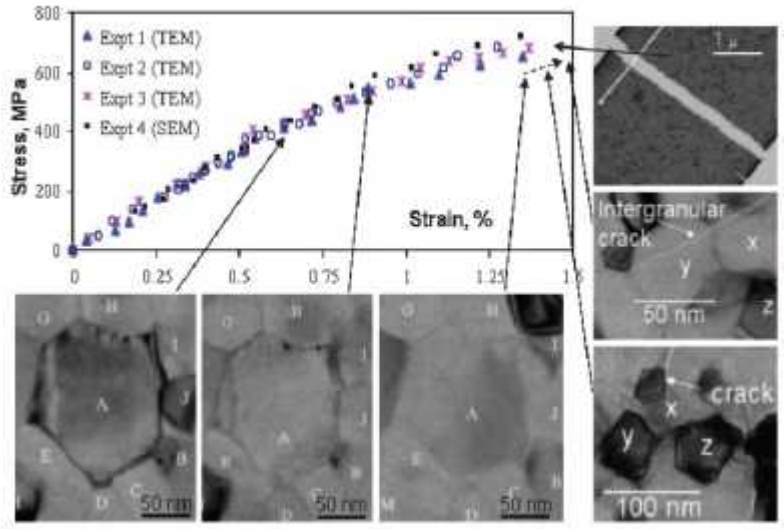
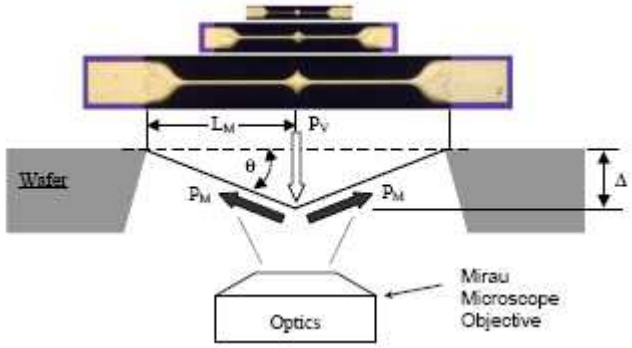
Many methods for micro and nanoscale mechanical testing are being developed

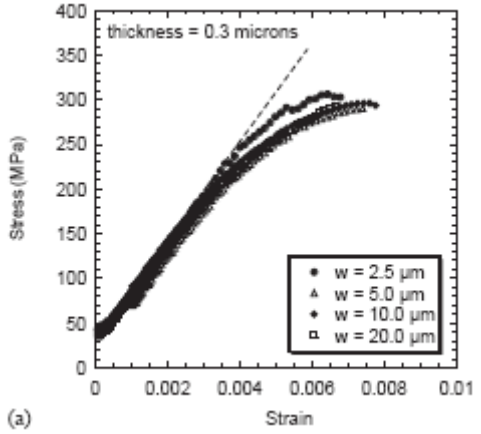




In-situ TEM

Haque and Saif (PNAS, 2004)





Membrane Deflection

Espinosa et al. (JMPS, 2004)

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Each method requires an external actuator and time-consuming aligment procedures

Consider a prototypical MEMS device (μrelay) to determine important mechanical properties

IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 8, NO. 8, AUGUST 1998

Performance of Low-Loss RF MEMS Capacitive Switches

Charles L. Goldsmith, *Senior Member, IEEE,* Zhimin Yao, *Member, IEEE,* Susan Eshelman, *Member, IEEE,* and David Denniston, *Member, IEEE*

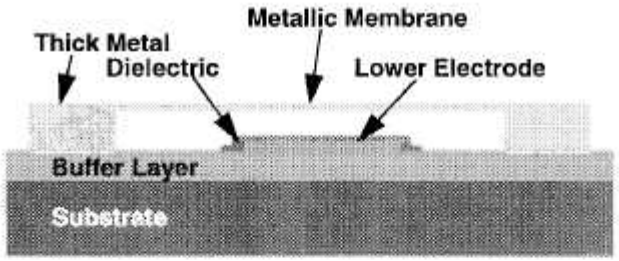

Fig. 1. Cross section of an RF MEMS capacitive switch.

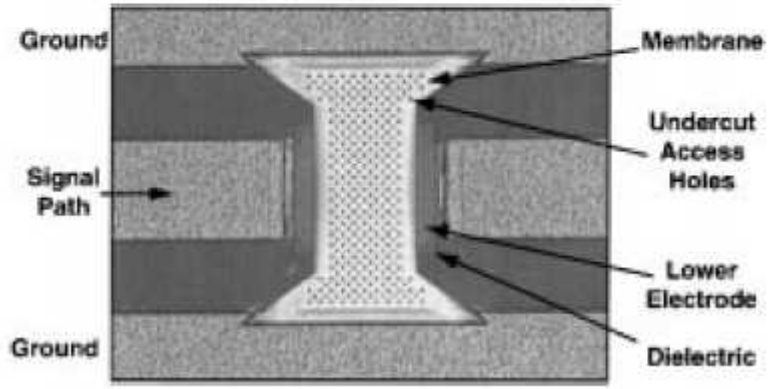

Fig. 2. Top view of a shunt MEMS capacitive switch.

Important characteristics:

1) Speed
2) Low Voltage
3) Large pull-off force
4) No change in performance

Performance depends on these mechanical properties:

1) E (Young's Modulus)
2) σ_R (residual stress)
3) σ_Y (yield strength)
4) σ_F (fatigue strength)
5) σ_C (creep limit)

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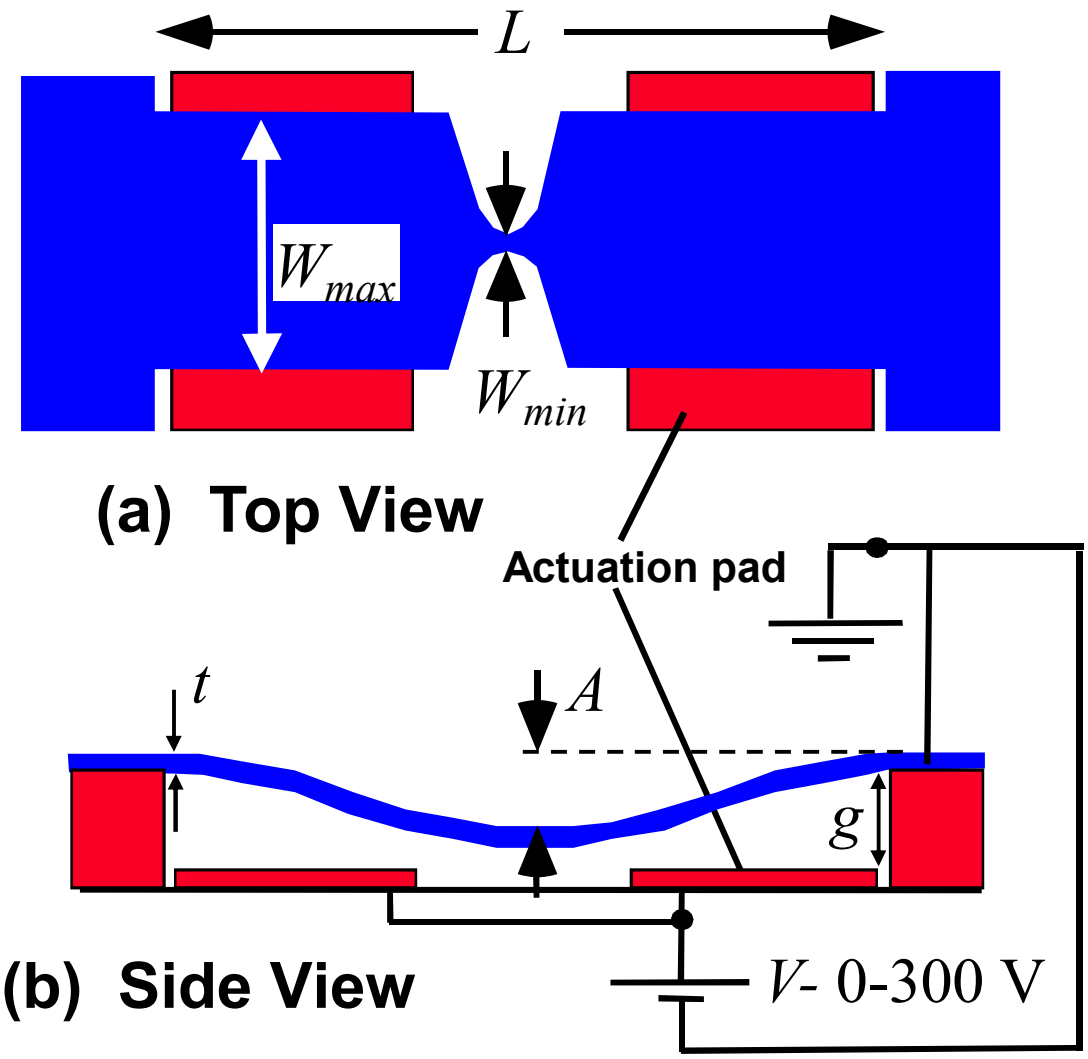
Propose a notched, fixed-fixed beam structure to study the mechanical limits



Advantages:

electrostatic actuation:

- contactless
- high cycles
- sample handling easy
- automatic testing possible

mechanical force amplification
→ small area (500 μm x 100 μm)

thin films (0.2 – 0.65 μm)

Device	W_{max}	W_{min}
1	50 μm	2.2 μm
2	50	8.2
3	50	18.2

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MEMS – surface micromachining implementation

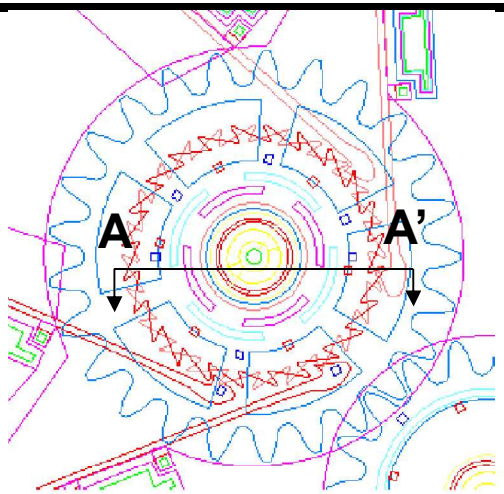
A series of structural and sacrificial layers are deposited

Ground plane layer (Poly 0)
4 structural levels
(Poly 1 - Poly 4)

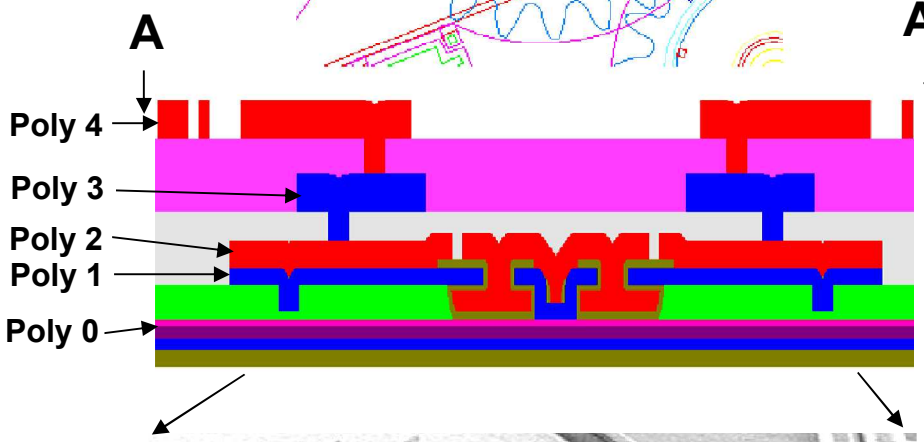
Chemical Mechanical Planarization (CMP)

1 μm design rule

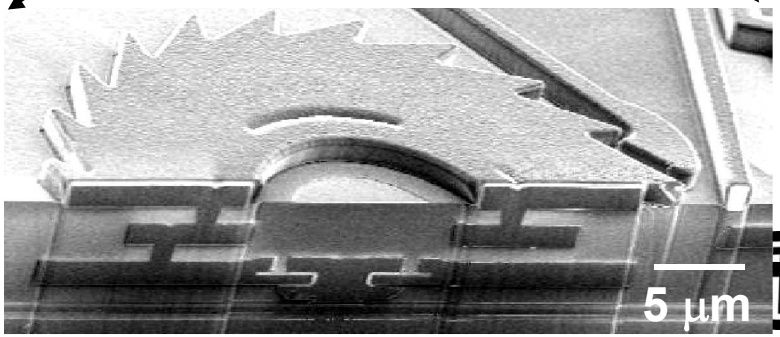
Create freestanding thin film structures by "release" process



Design



Cross-section drawing



FIB cross-section

Sniegowski & de Boer, Annu. Rev. Mater. Sci. (2000)

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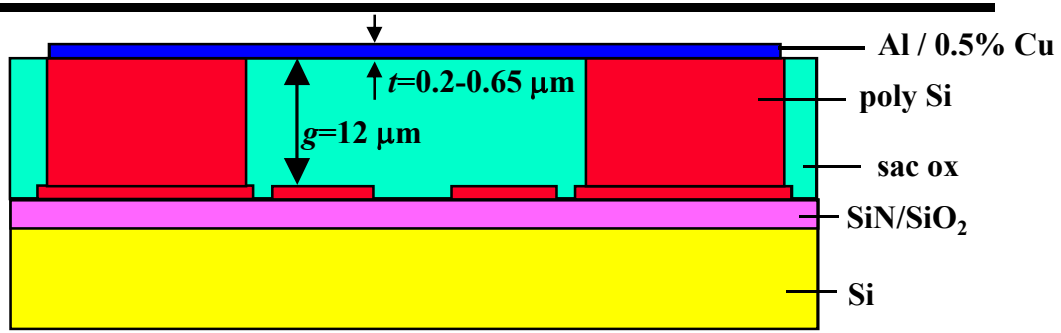
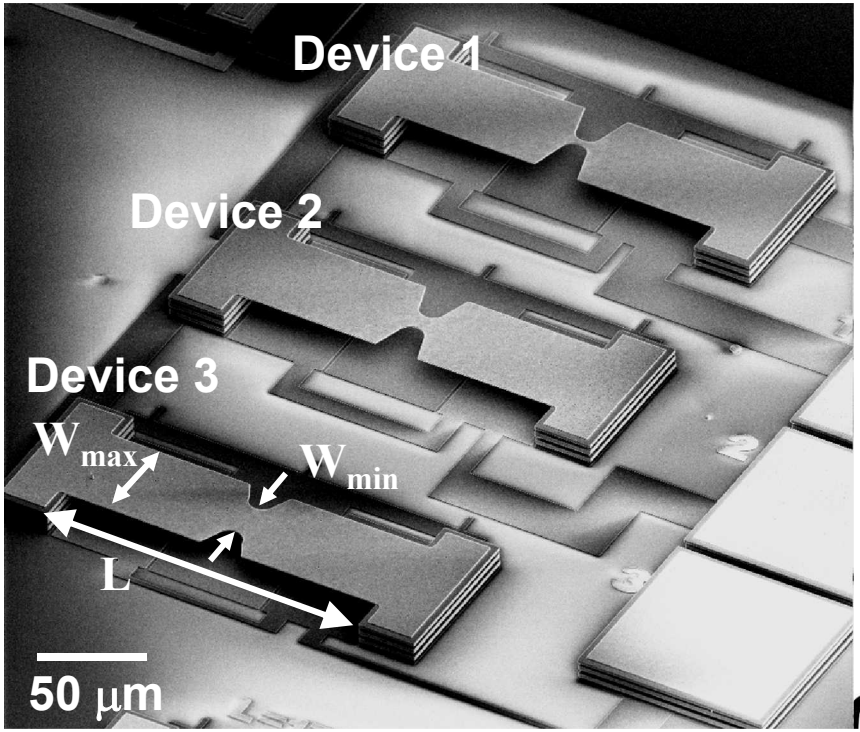
Sample Fabrication



SEM
(L=160 µm, W_{min}=18.2, 8.2, 2.2 µm)



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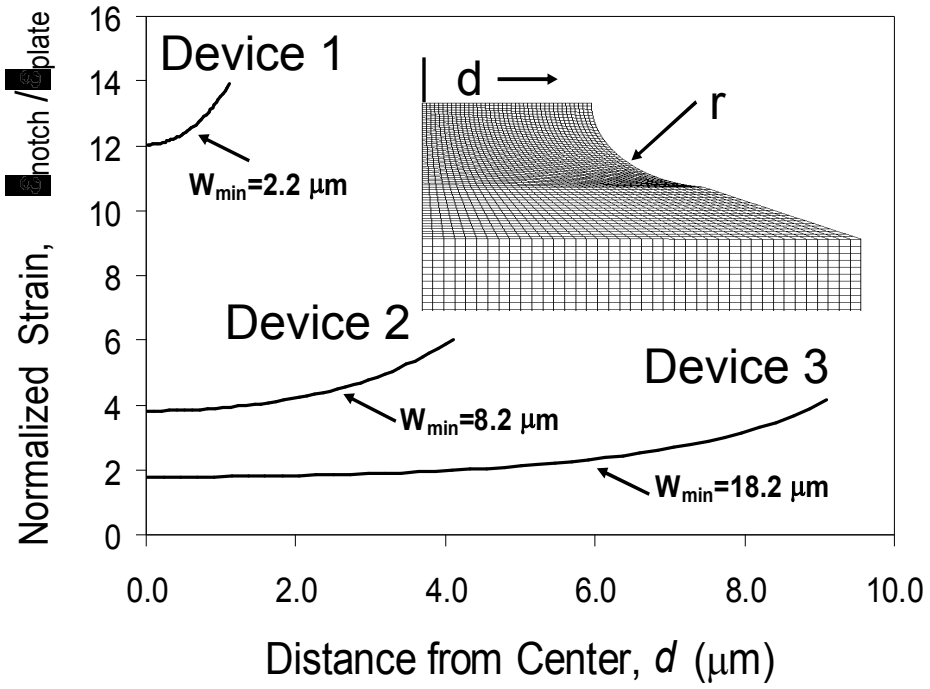
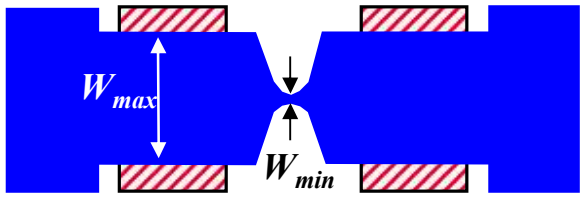
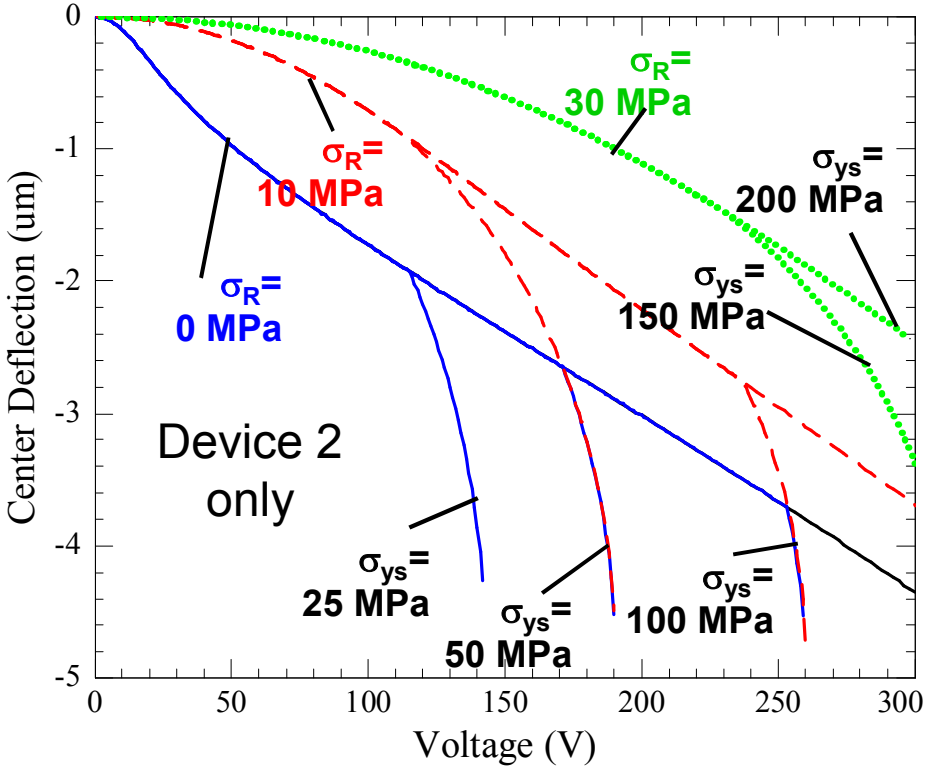
Mechanics simulations

Stress concentration due to residual or applied stress (2-D FEM)





Elastic-plastic behavior in the presence of applied electrostatic load (quasi 3-D model)



De Boer et al., Part I (Acta Mater. 2008)

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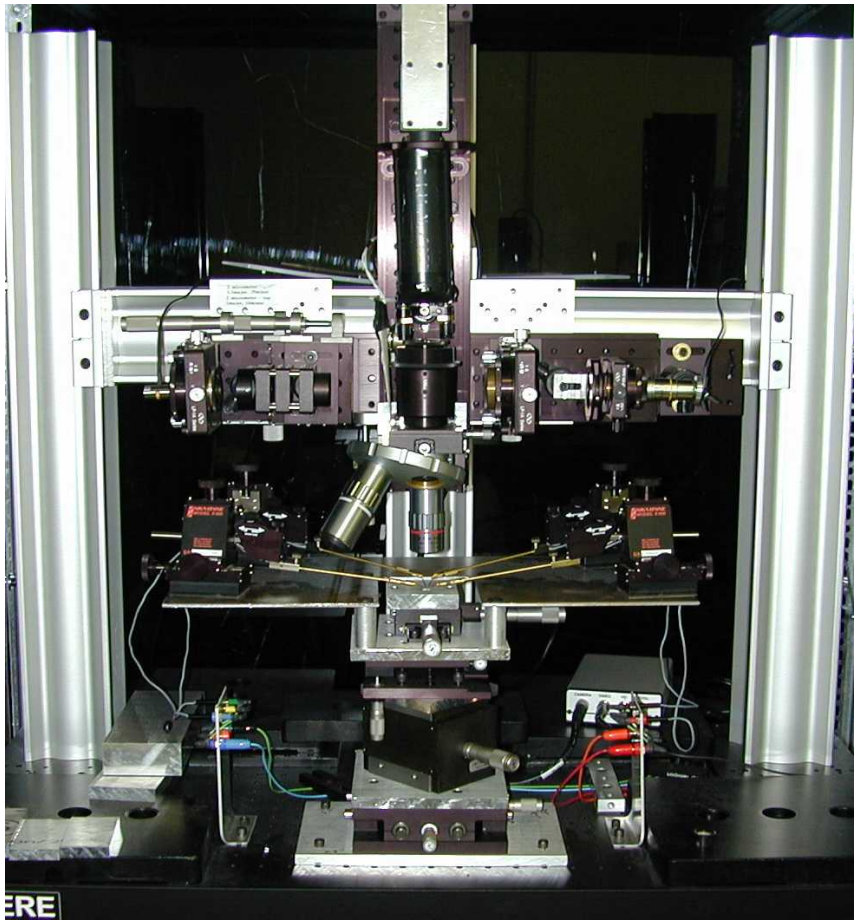
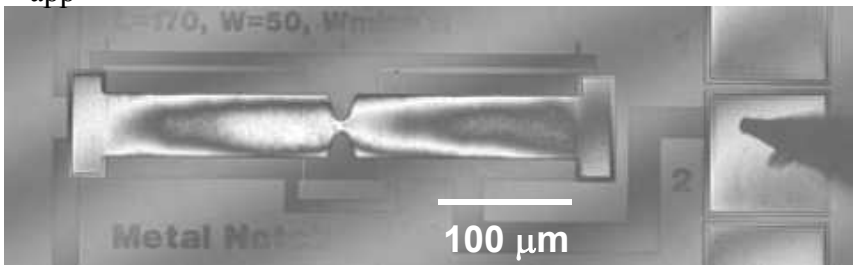
Testing

High-Resolution Probe Station
(Sinclair, Corwin & de Boer, Appl. Optics, 2005)

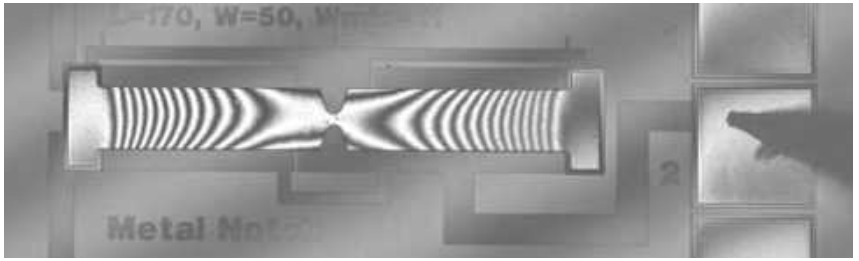


Interferograms (L=360 μm, W_{min}=8.2 μm)

V_{app}=0 V



V_{app}=290 V



use phase-stepping interferometry to measure the deflections (full-field technique)

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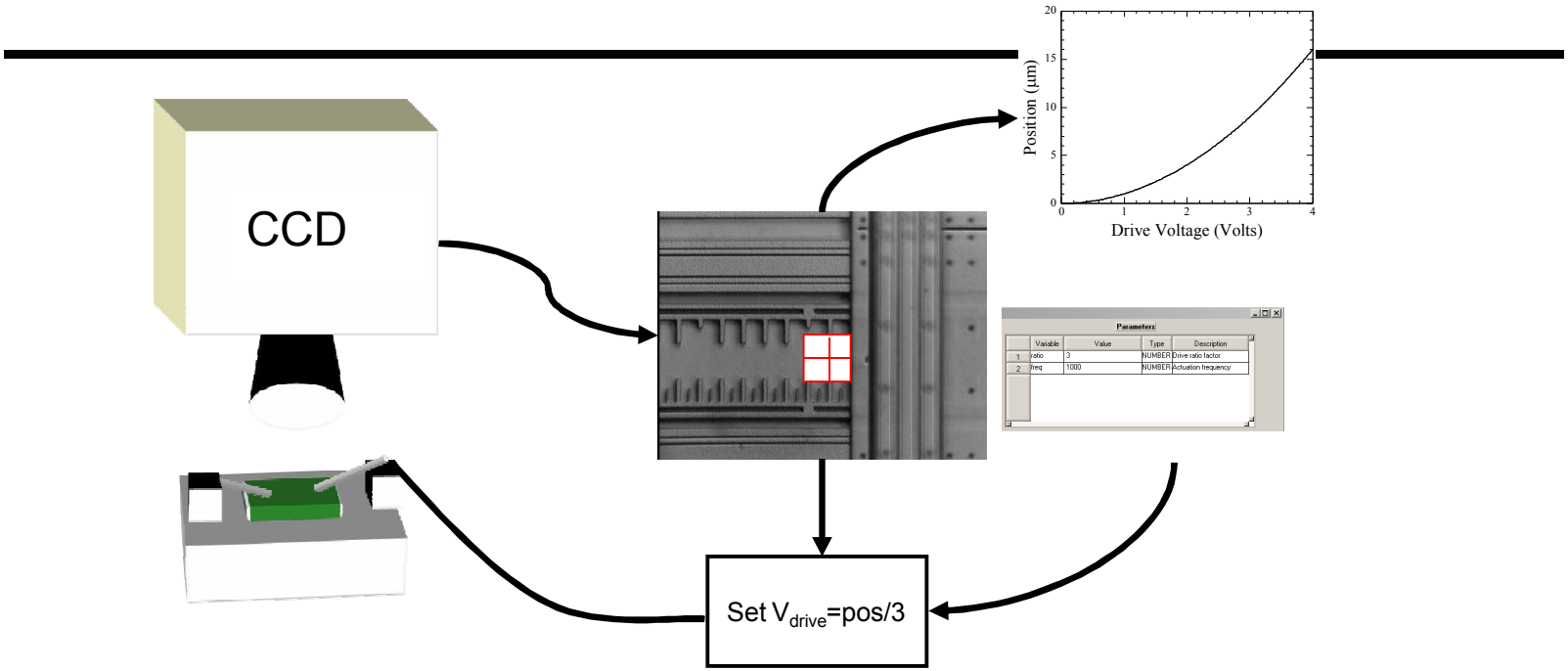
MEMS*cript*

An integrated vision and actuation automation tool for MEMS



Intelligent Actuation: Combine real time in-plane, interferometric, and stroboscopic vision capabilities with full scripting power to allow actuation to respond to vision data in real time

Flexibility: Works with a variety of National Instruments image capture and digital to analog boards, as well as GPIB and serial devices. Interface to external programs via DDE (i.e. LabView)

Simplicity: Presents simple user interface to allow use without knowing scripting language

Power: Full featured scripting engine written in C includes full branching (make decisions on the fly), arithmetic function evaluation (calculate on the fly), graphing (display on the fly), file output (save data and images for further analysis/presentation)

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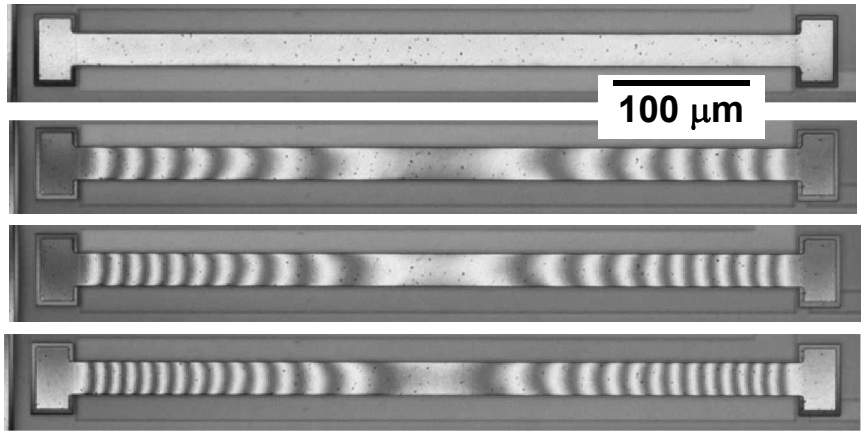
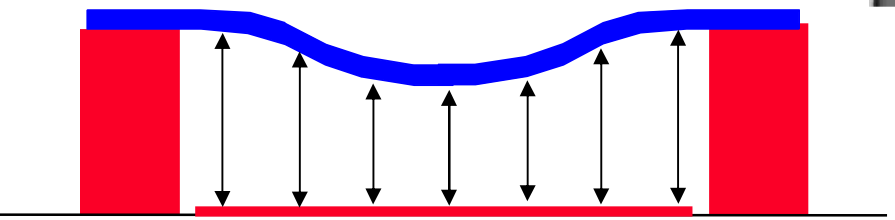
Assess the residual stress with a fixed-fixed beam geometry

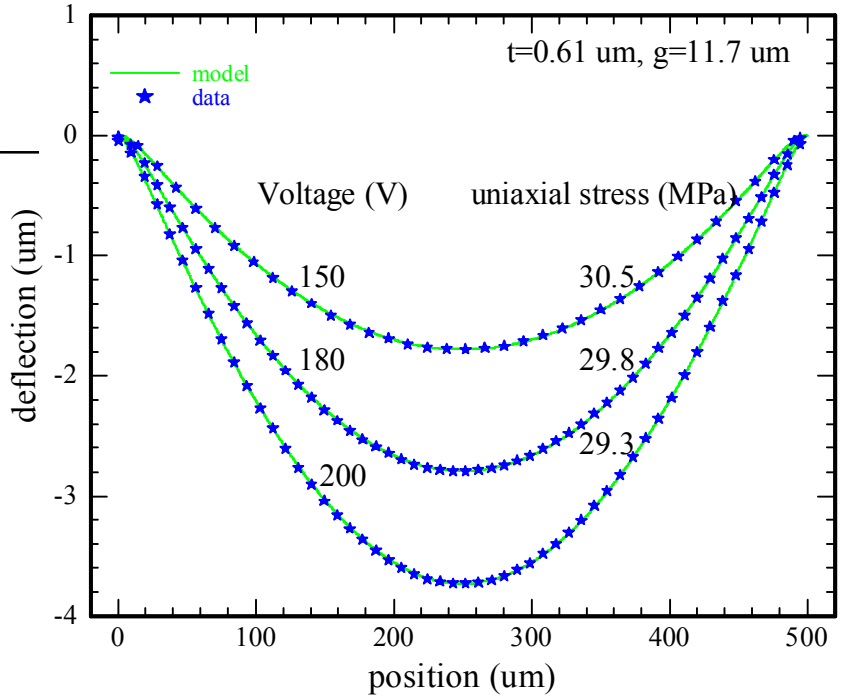
Interferograms



Apply electrostatic load

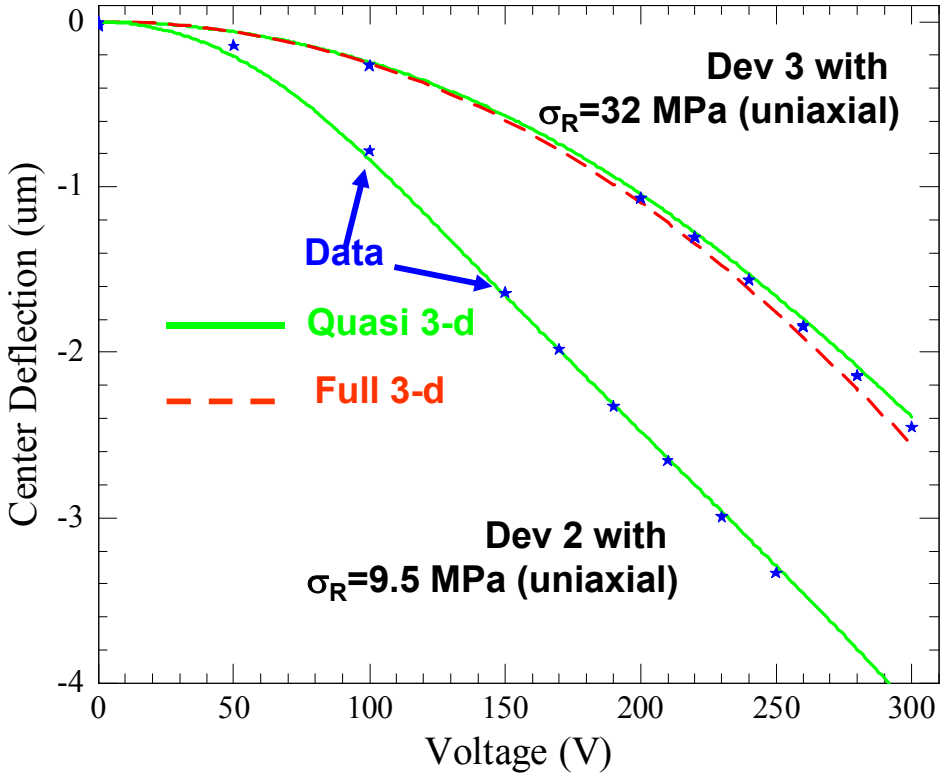


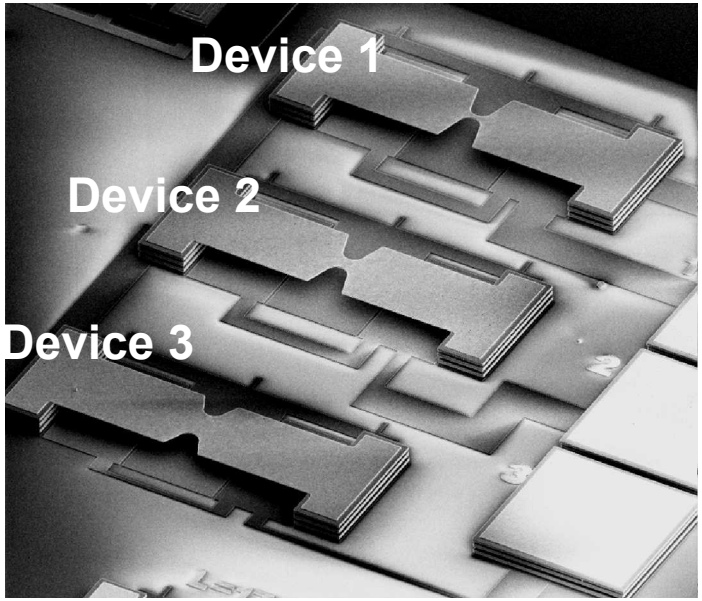
Measured & Modeled Deflections



(r3568_r2c1)

Device 3 residual stress agrees with versus ff beam, but Device 2 residual stress is lower





De Boer et al., Part II (Acta Mater. 2008)

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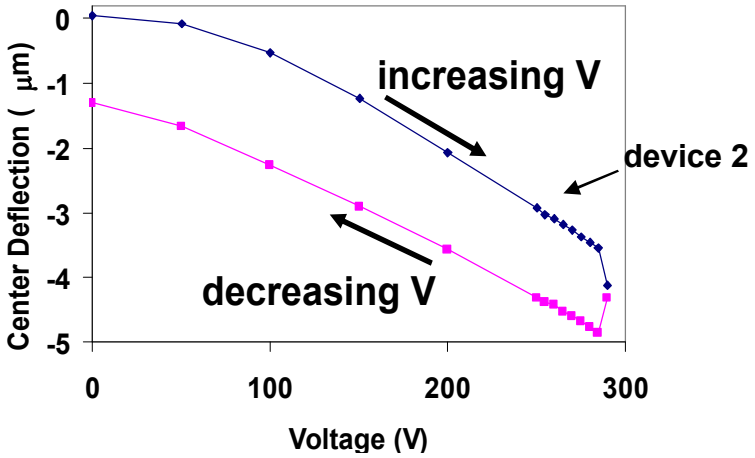
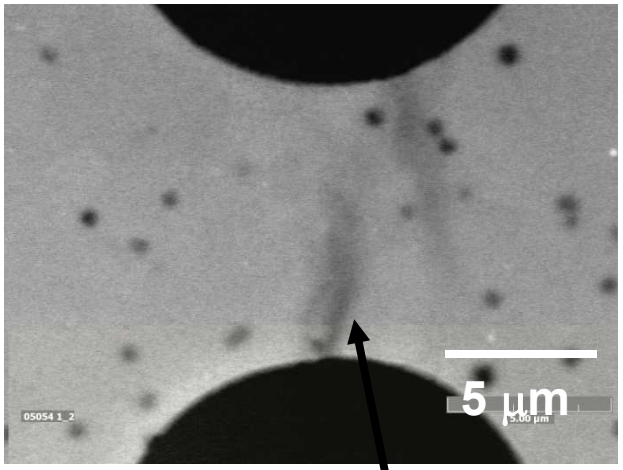
Device 2 exhibits plastic behavior at slightly higher loads (290 V)

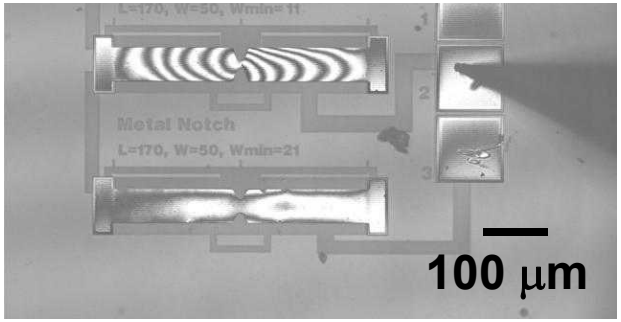
Large Hysteresis (~1.5 μm)



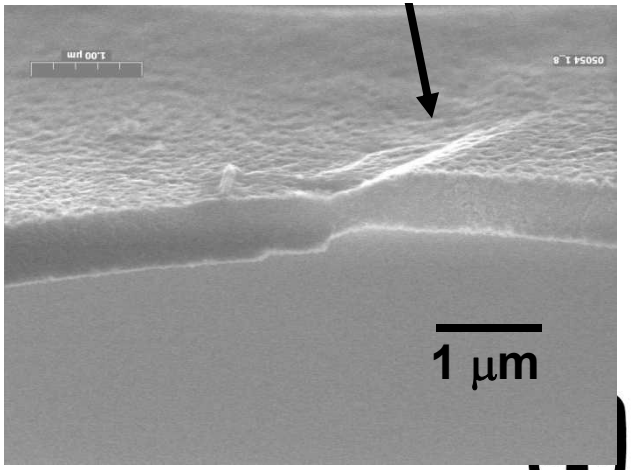
SEM backscatter image



Interferogram (after actuation)



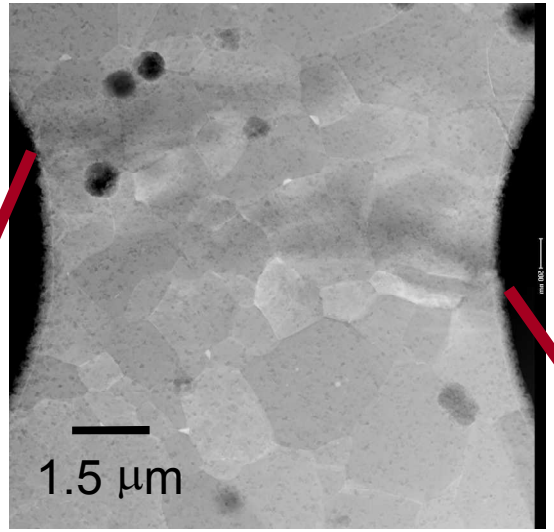
Tilted SEM image



σ_{ys} ~150 MPa in heavily strained notch zone

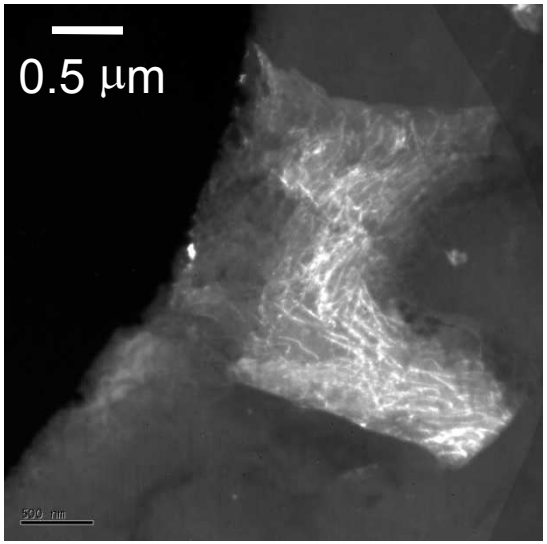
Ex-situ TEM of plastically deformed Device 2

Notch region

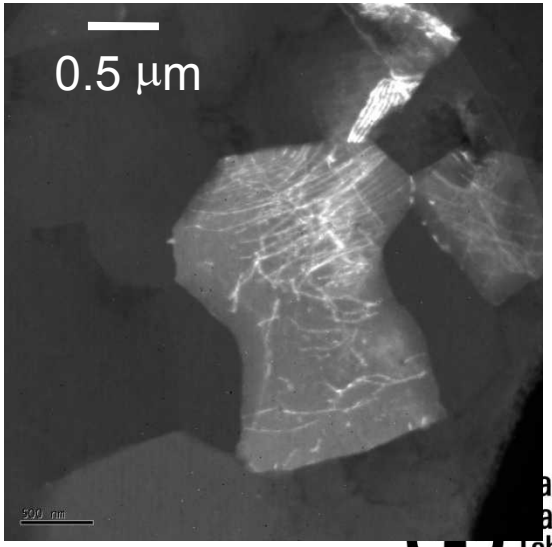


(STEM ADF)

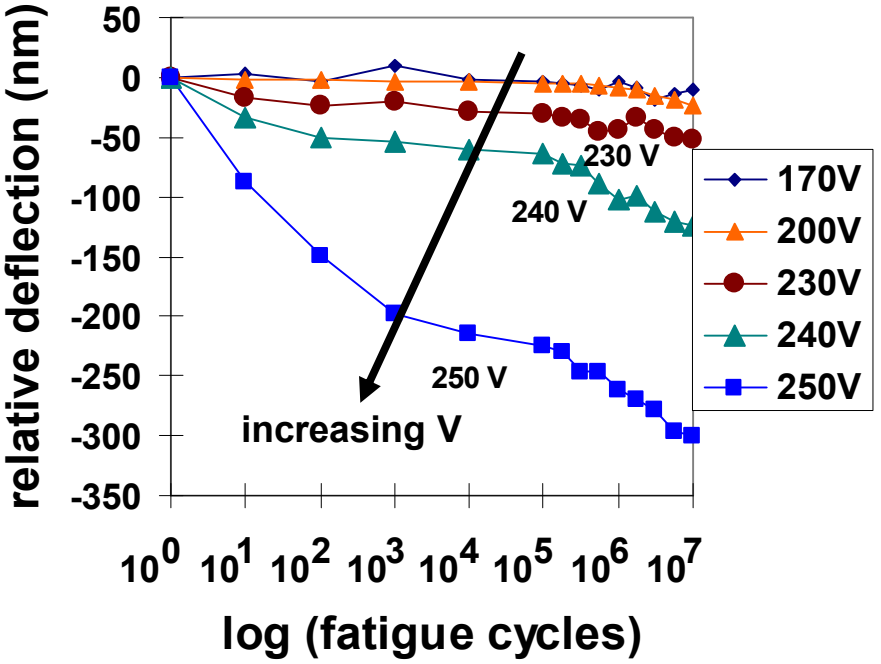
(Dark Field)



(Dark Field)



Device 2 fatigues
TEM: striations observed



Procedure

1) Fatigue for N cycles, N=1, 10, … , 10^7
   - at fixed dc voltage
   - with 10 V ac voltage modulation at 10 kHz
2) Apply DC voltage and measure center deflection
3) Repeat (1) & (2) to 10^7 cycles (20 minutes)
4) Choose new voltage and repeat (1)-(3)

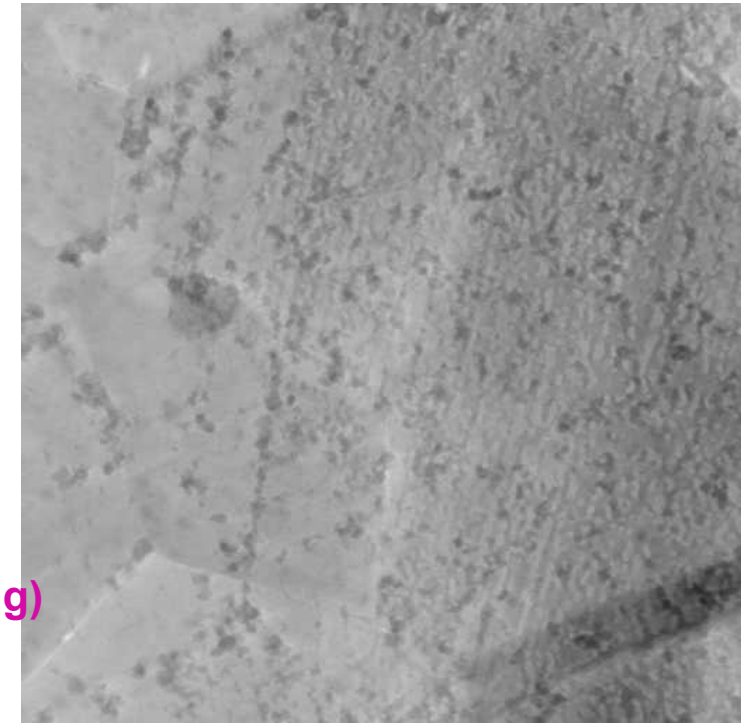
Notes:

All data on graph from one device

DC voltage changed randomly from test to test (not monotonically)

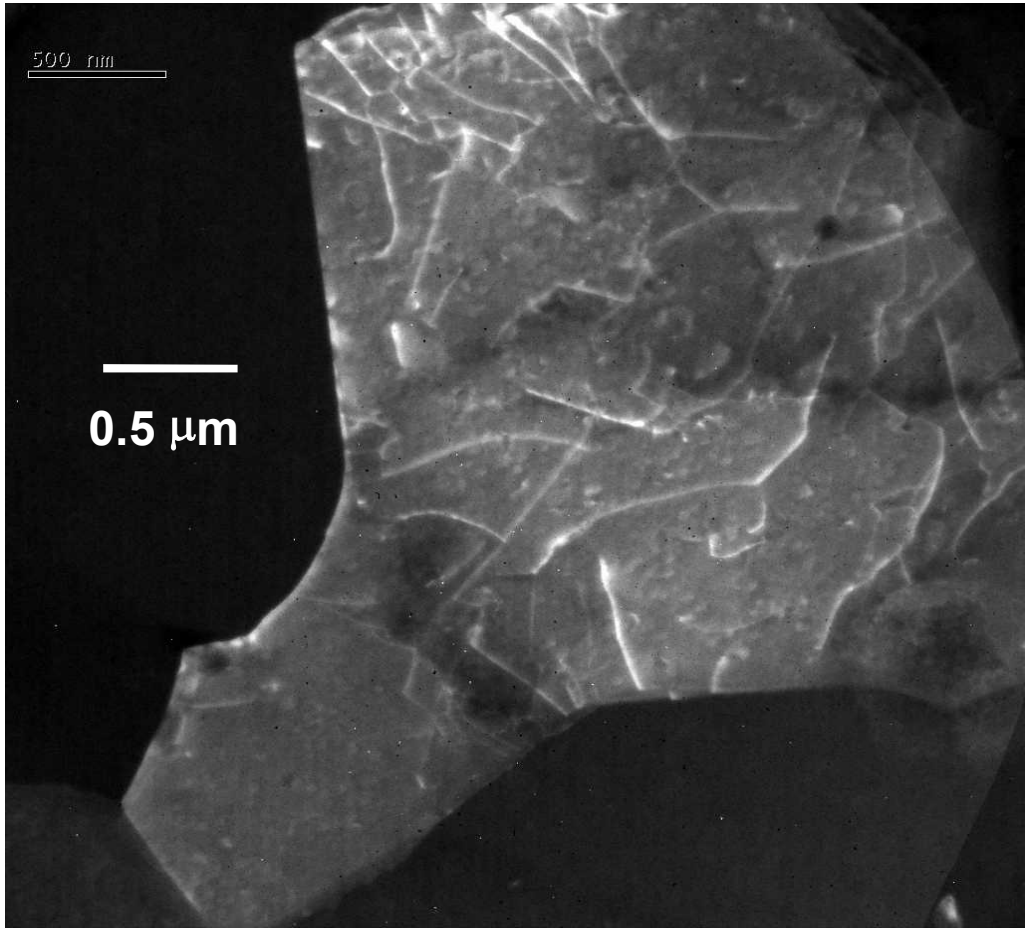
10 kHz modulation frequency is well below resonance

- no amplitude enhancement (stroboscopic monitoring)



De Boer et al., Part II (Acta Mater. 2008)

Device 3 does not exhibit fatigue



Fatigued up to 10^9 cycles

No change in deflection curves

Lower bound for fatigue strength is 172 MPa

Background dislocation density in Device 3 sample is ~$10^9/cm^2$

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Summary – thin film metal testing

Developed an on-chip laboratory kit for easy testing of thin film metal structural materials

Can assess E, residual stress, strength, fatigue, (creep)

Many more experiments possible

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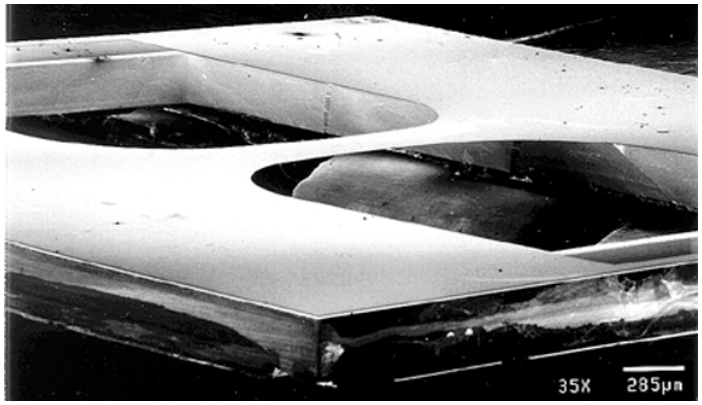
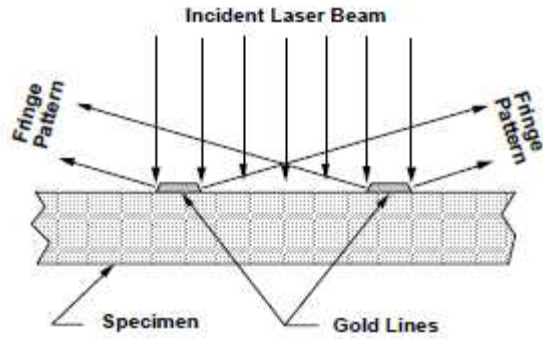
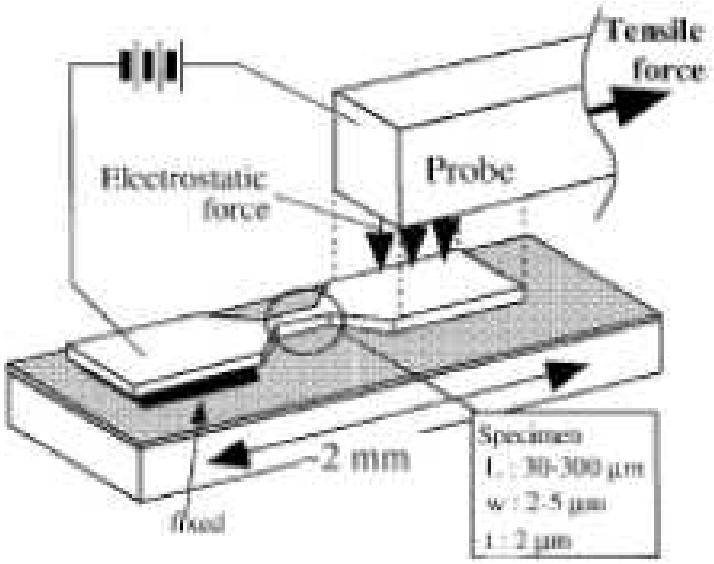
Testing of brittle materials

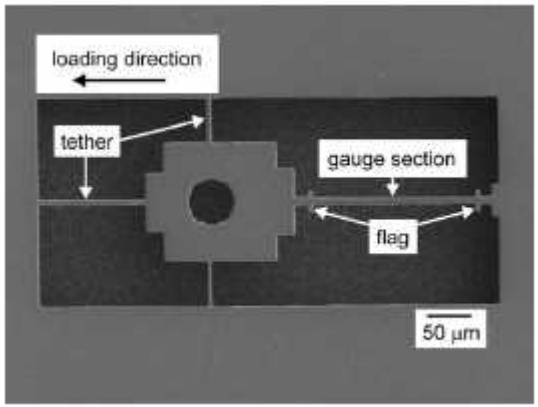




Sharpe
JMEMS 1996



Tsuchiya
JMEMS 1996



Read and coworkers
Scripta Mat 2003

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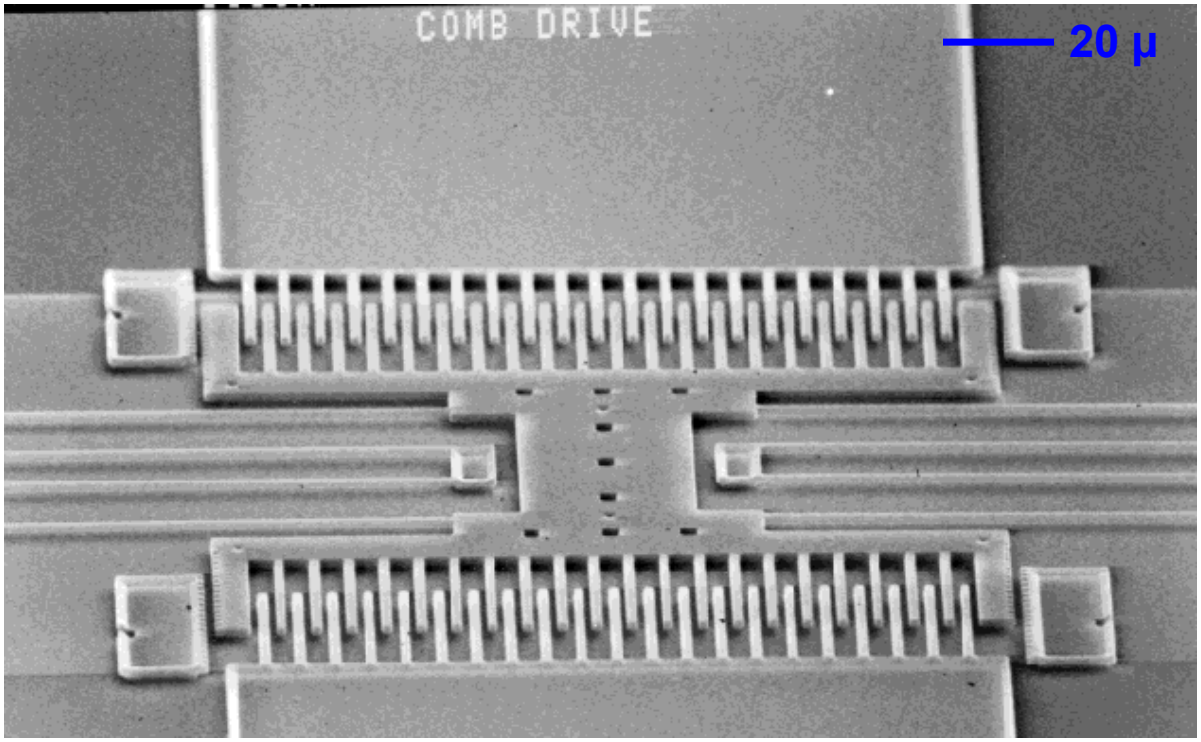
In-situ testing: How about comb drives?



It is Relatively Easy to Produce Motion.
It is Difficult to Perform Work!

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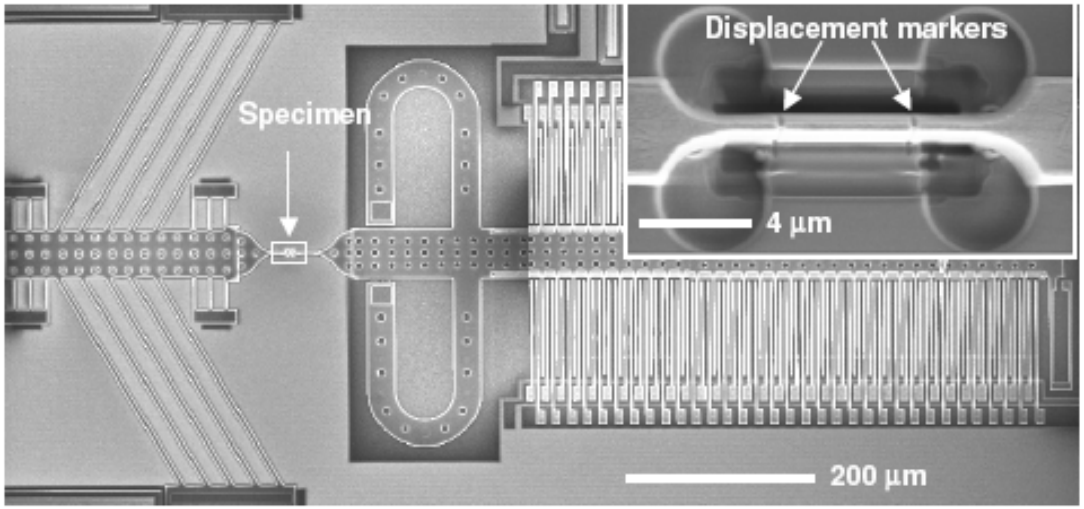
In-situ testing: Thermal actuators?

Zhu & Espinosa (JMM 2006)

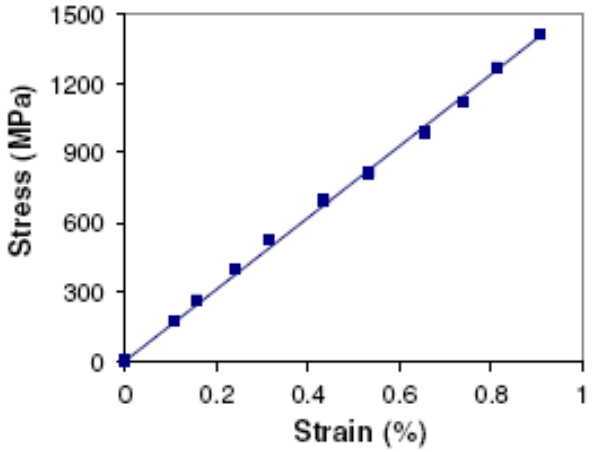


(*a*)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF MICROMECHANICS AND MICROENGINEERING
J. Micromech. Microeng. 16 (2006) 242–253 doi:10.1088/0960-1317/16/2/008

A thermal actuator for nanoscale *in situ* microscopy testing: design and characterization

Yong Zhu, Alberto Corigliano[1] and Horacio D Espinosa

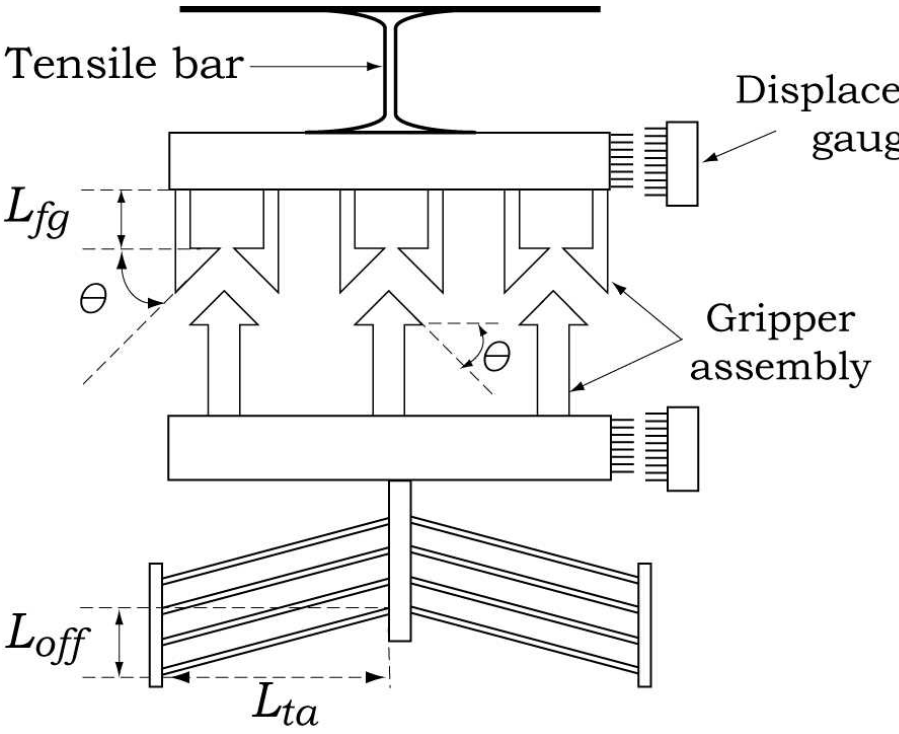


(*b*)

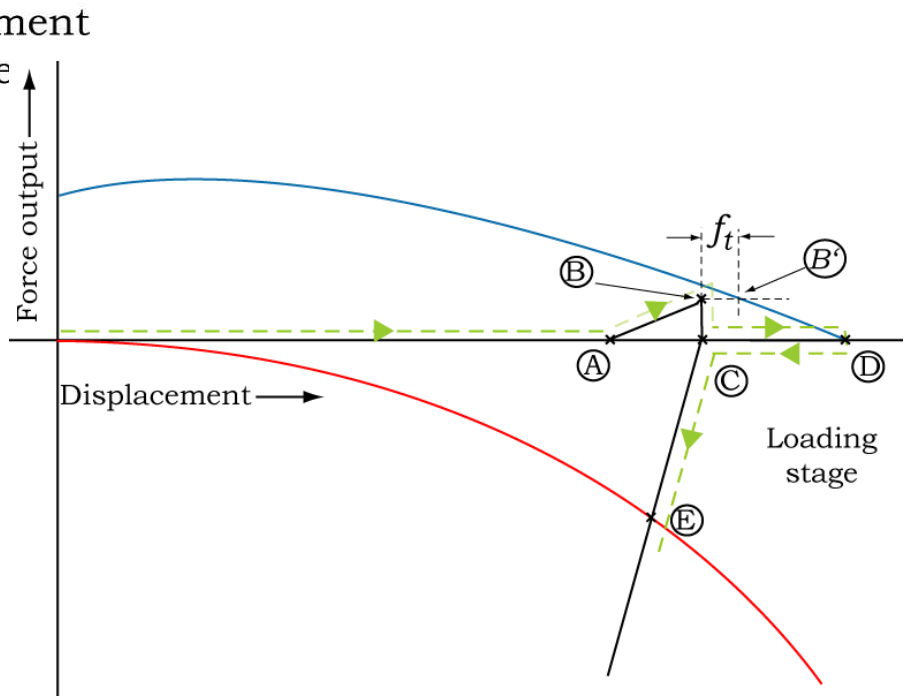
Related idea: cooling of a thermal actuator develops large on-chip forces

Loading schematic

gripper insertion: A to B
gripper engagement: D to C
tensile bar loading: C to E



Thermal actuator
force output $\in [3mN, 45mN]$



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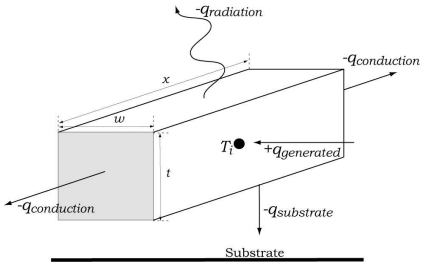
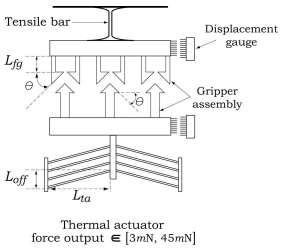
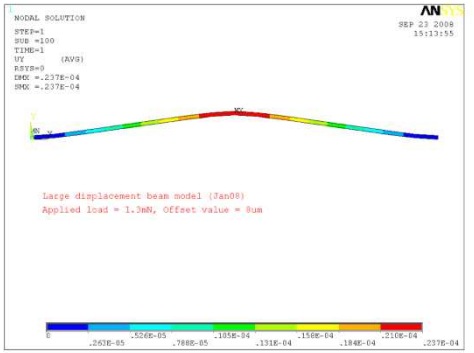
Matlab thermal model and ANSYS structural model (with some analytical calcs)

Matlab





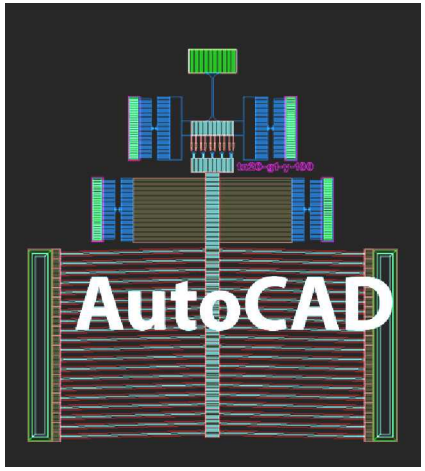
1

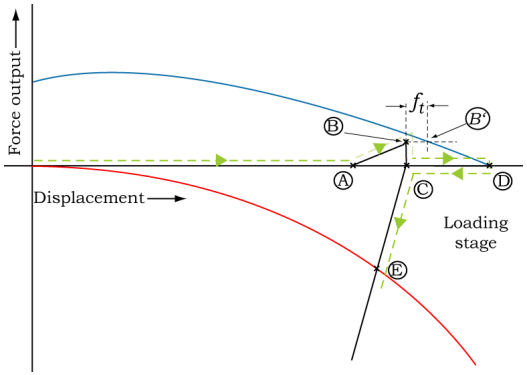


2 **ANSYS**

3n Optimization

Final design





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Model details

Grippers and T-bar:

Gripper geometry: θ=45°, L=30 μm, W=1 μm

5 pairs of grippers in each of 3 poly layers

Gripper Stiffness= 36627 N/m (analytical)

T-bar Stiffness= 7213 N/m (analytical, based on L_{Tbar}=100 μm)

Thermal Actuator:

Max Temp=600 °C

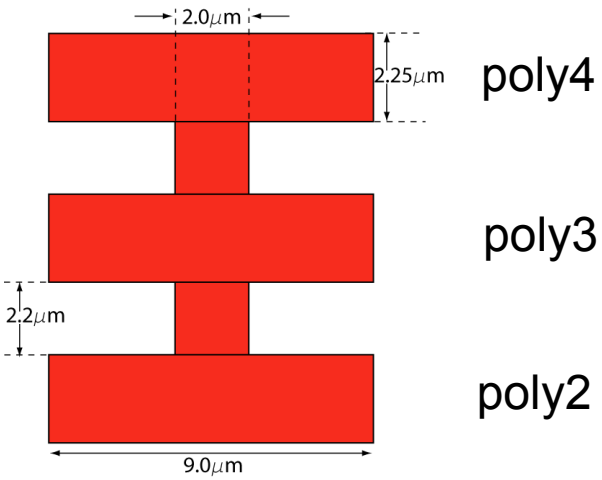
Residual stress included (15 MPa assumed)

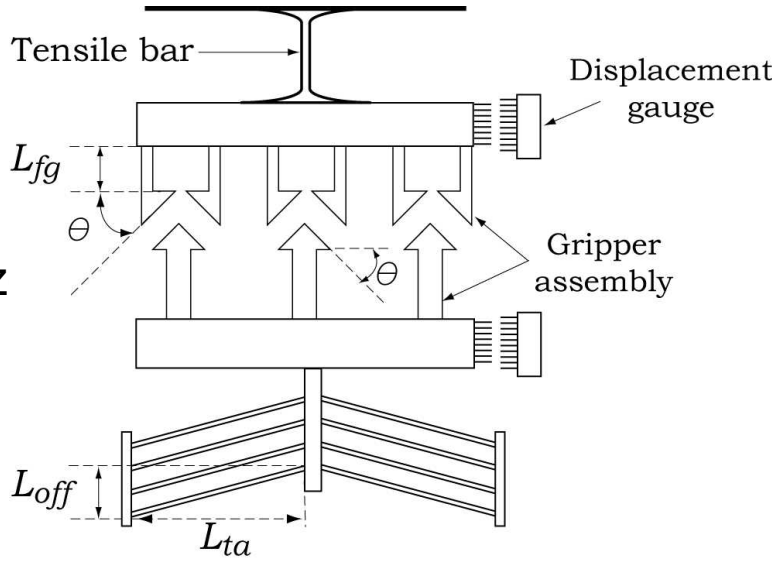
L_{ft}=0.5 μm

Leg length: 300 μm

Leg geometry: (make as wide as possible to maximiz force, but keep $2I_{zz}<I_{xx}$ to ensure in-plane buckling)

I_{zz}=385 μm^4, I_{xx}= 852 μm^4





Thermal actuator
force output $\in [3mN, 45mN]$

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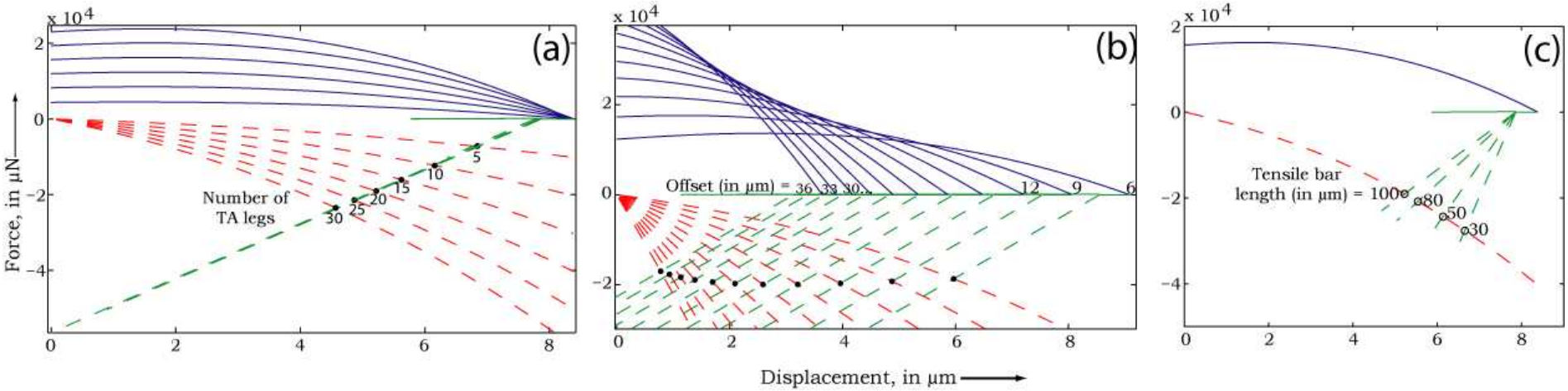
Parametric studies to optimize the design



Increasing the number of TA legs increases the force. Each successive red curve is a simple superposition of the previous curve. The force increases nonlinearly because of the compliance of the tensile bar, so we want to choose an optimum number of TA legs.

***Baseline*: 20 legs**

***Range*: 10-30 legs**

As offset increases, max displacement decreases. But linear stretching increases, resulting in higher force at same displacement. Considering sample compliance, the net effect is small.

***Baseline:* 8 μm (area limit)**

***Range:* 15, 17, 20 μm**

Shorter T-bar decreases compliance, resulting in higher force.

***Baseline:* 100 (70) μm (fillet effect)**

***Range:* 0, 30 (16) , 100 (70) μm**

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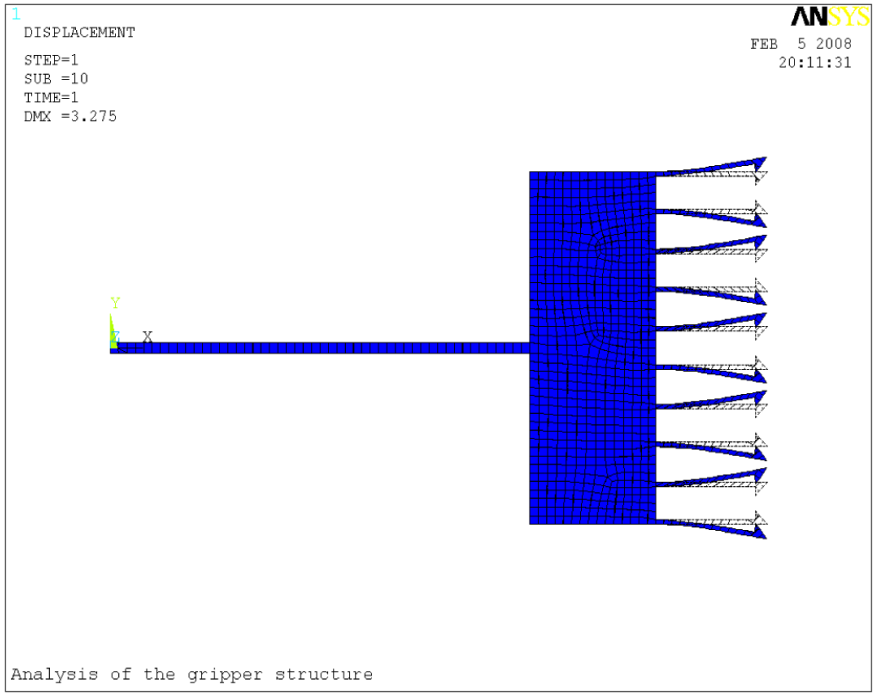
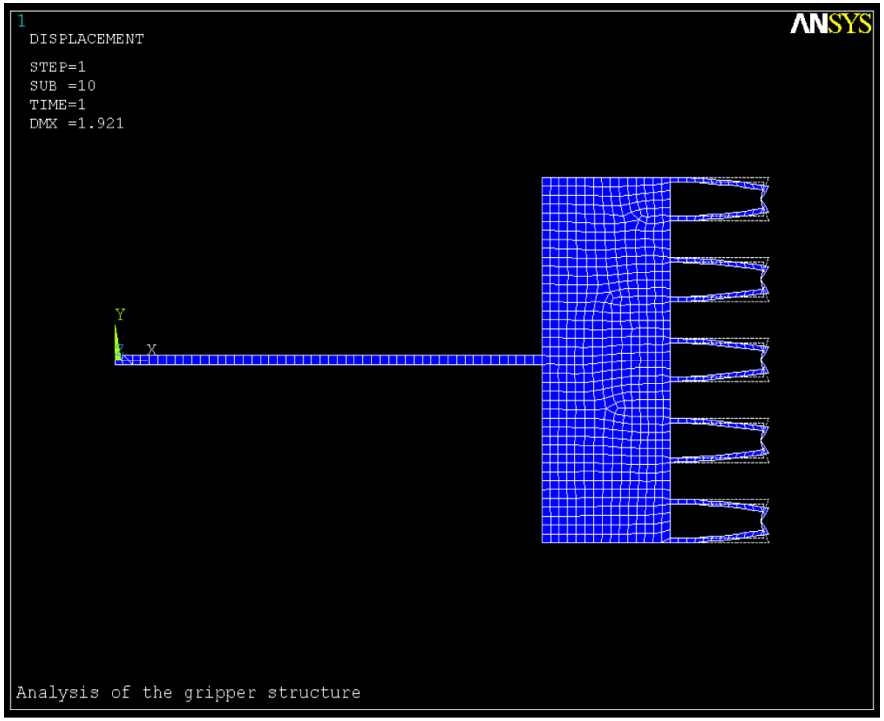
ANSYS modeling of gripper insertion

Gripper deflection



Effect of friction on grips (μ=0.5, θ=25°)



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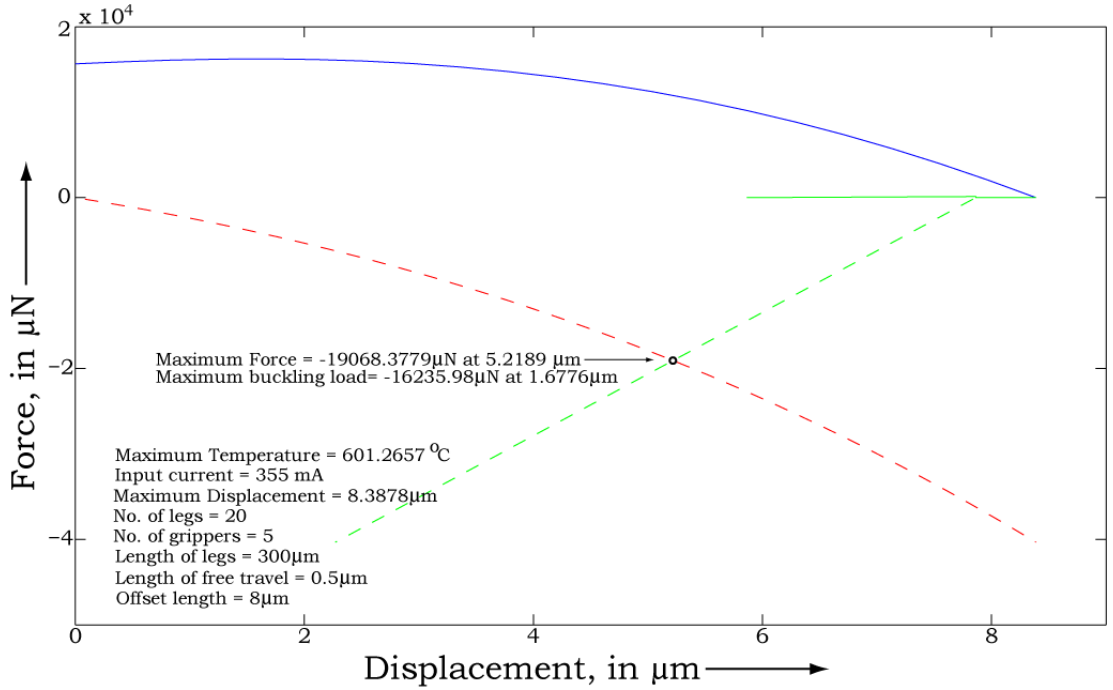
To-scale theoretical model of baseline device with 20 TA legs



$$\frac{20 \cdot 10^{-3}\ \mathrm{N}}{4 \cdot 10^{-12}\ \mathrm{m}^2} = 5\ \mathrm{GPa}$$

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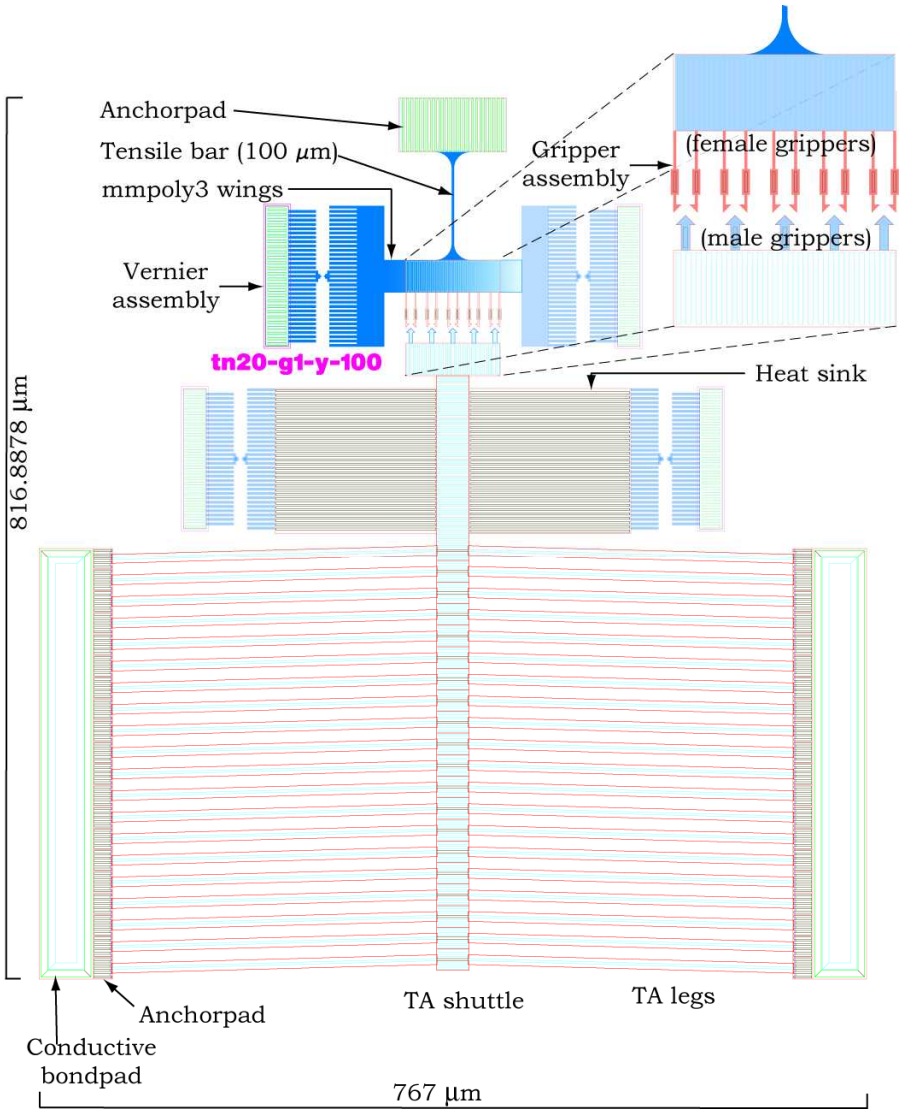
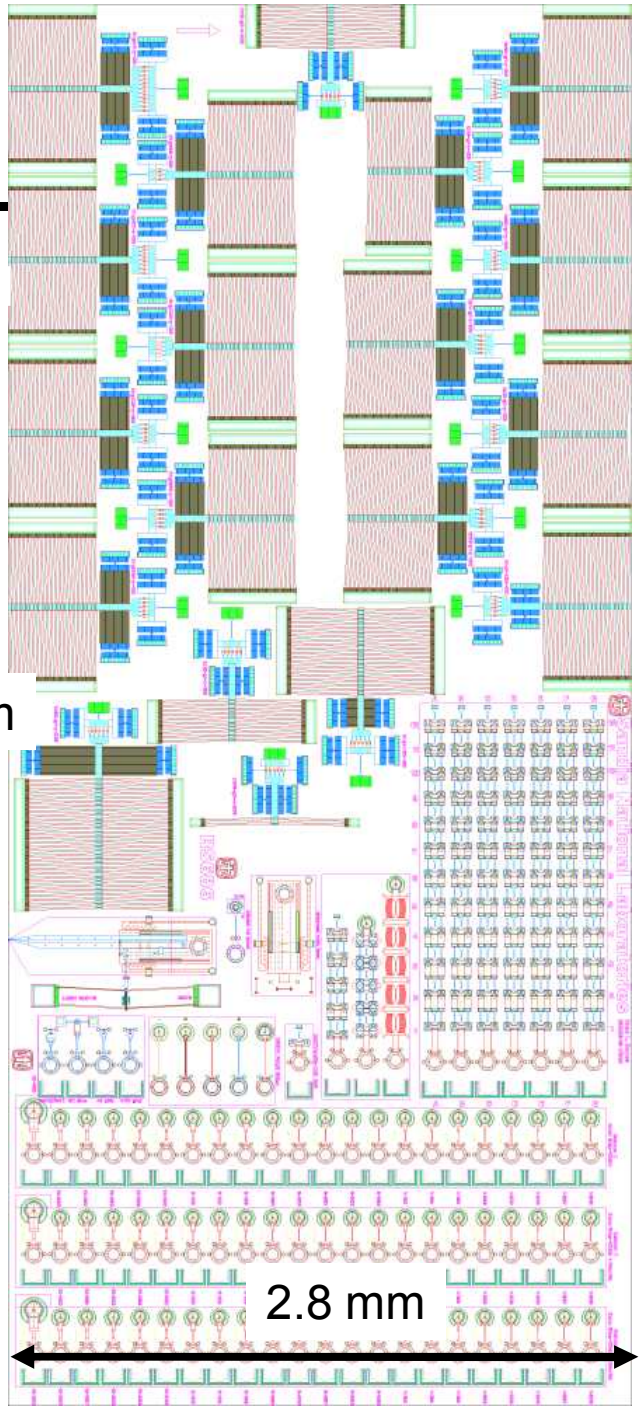
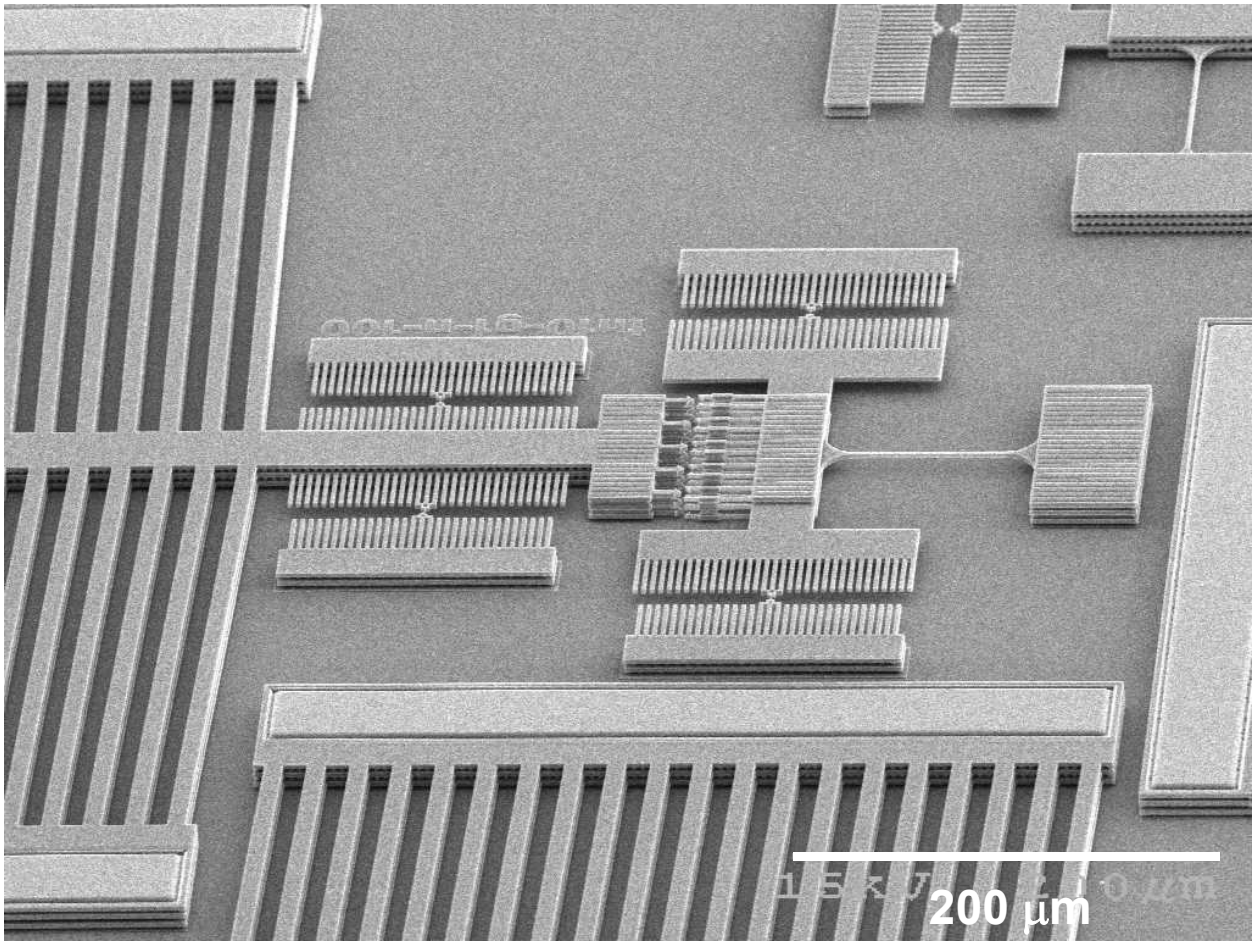
SUMMiT V™ test chip layout





SEM image of fabricated and released device



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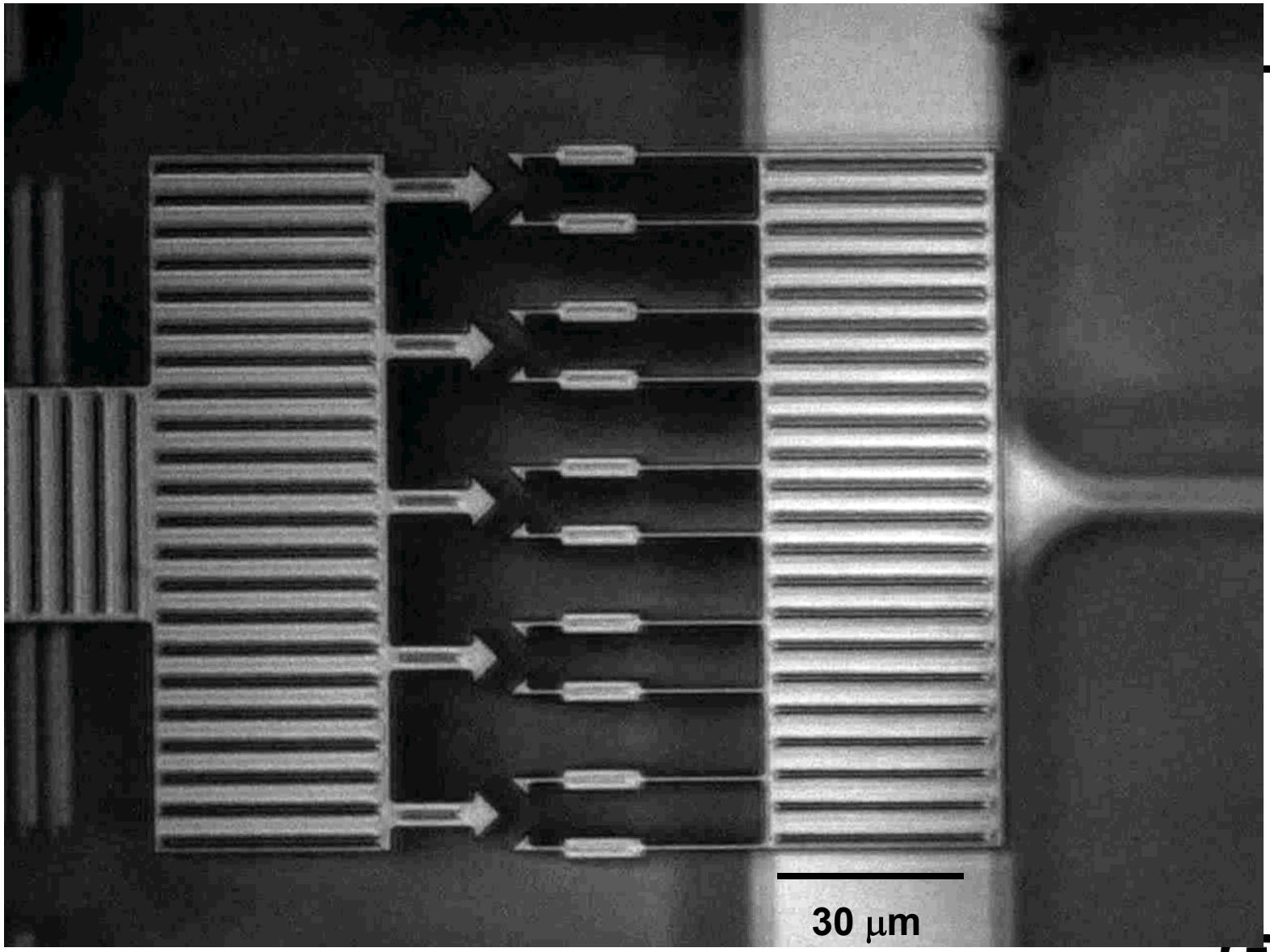
Gripper insertion movie (Optical, 50X)



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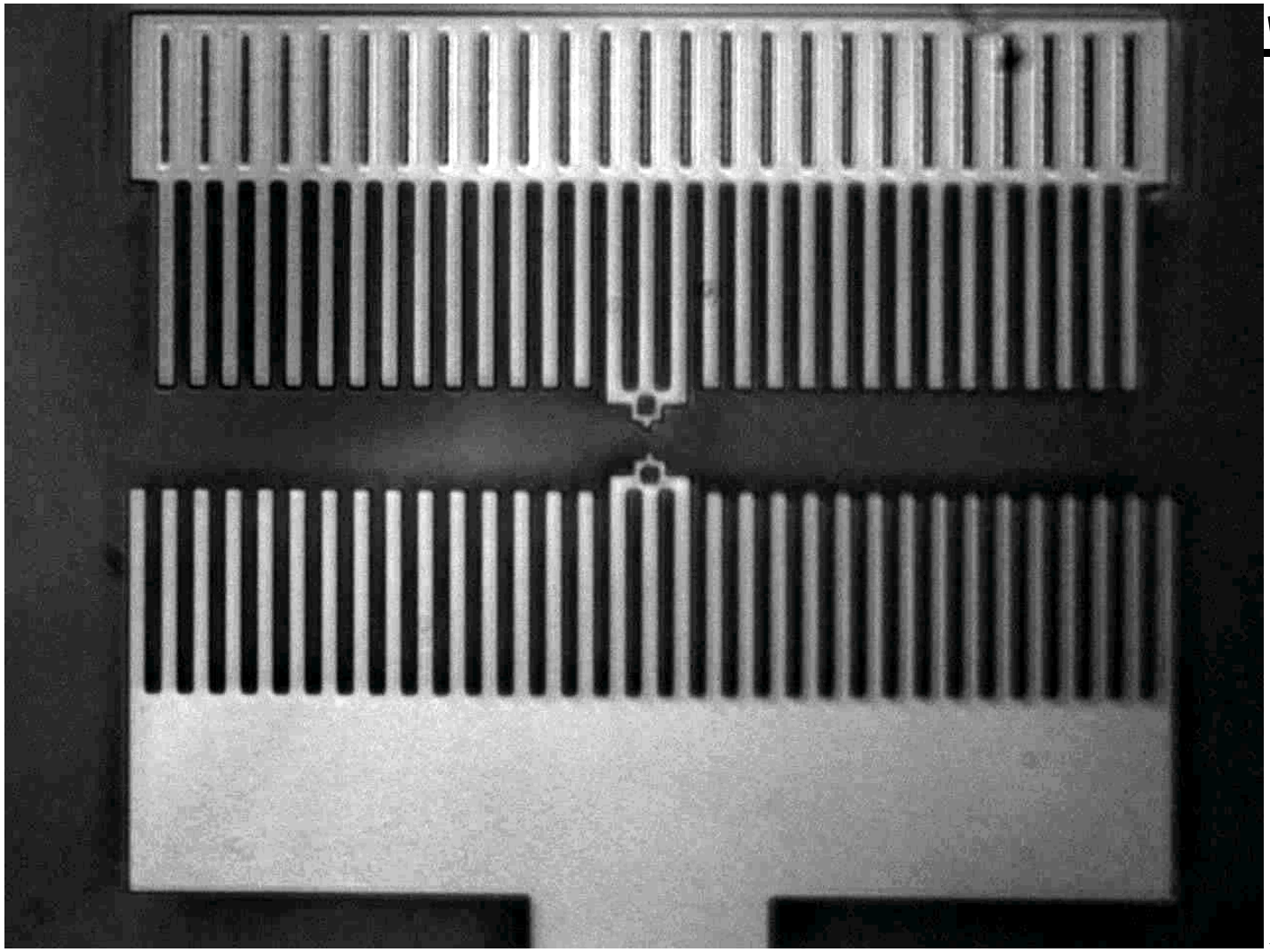
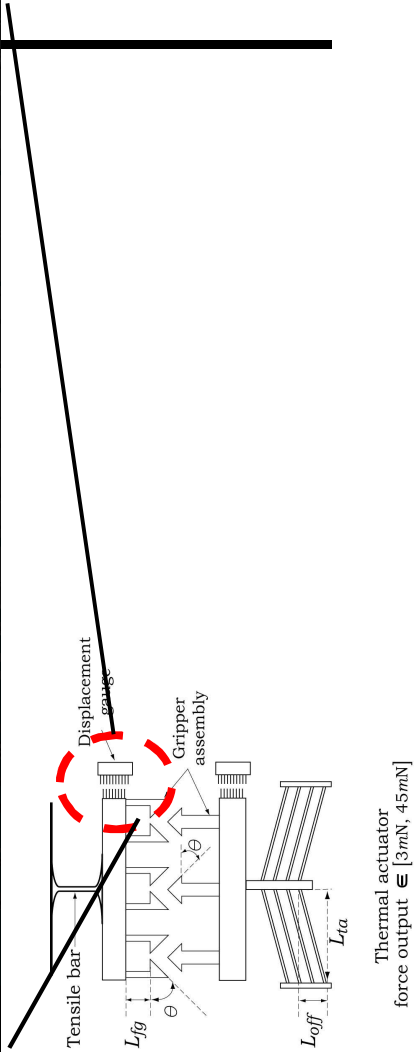
Tensile-bar extension movie (Optical, 50X)





25 μm

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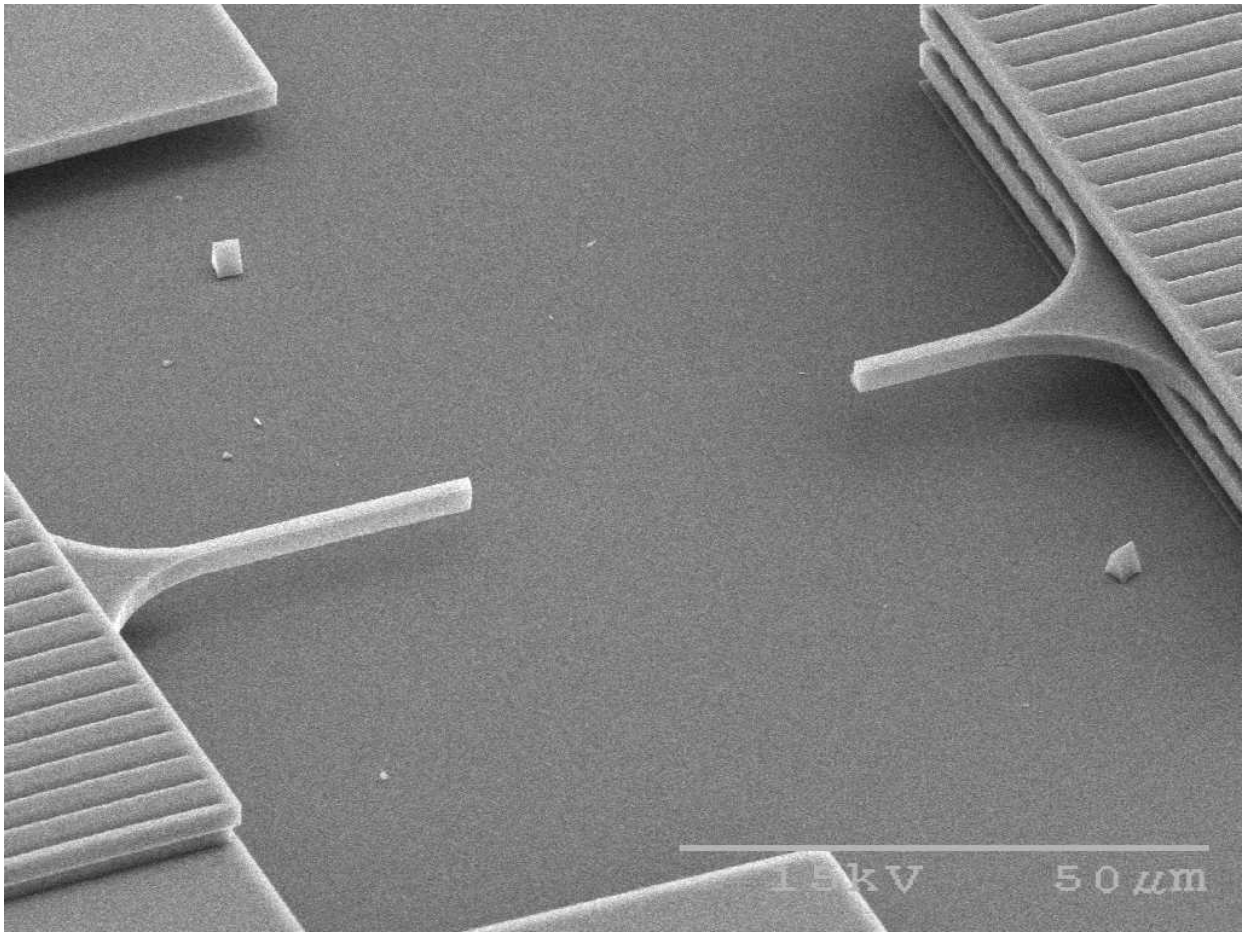
Fractured Tensile bar



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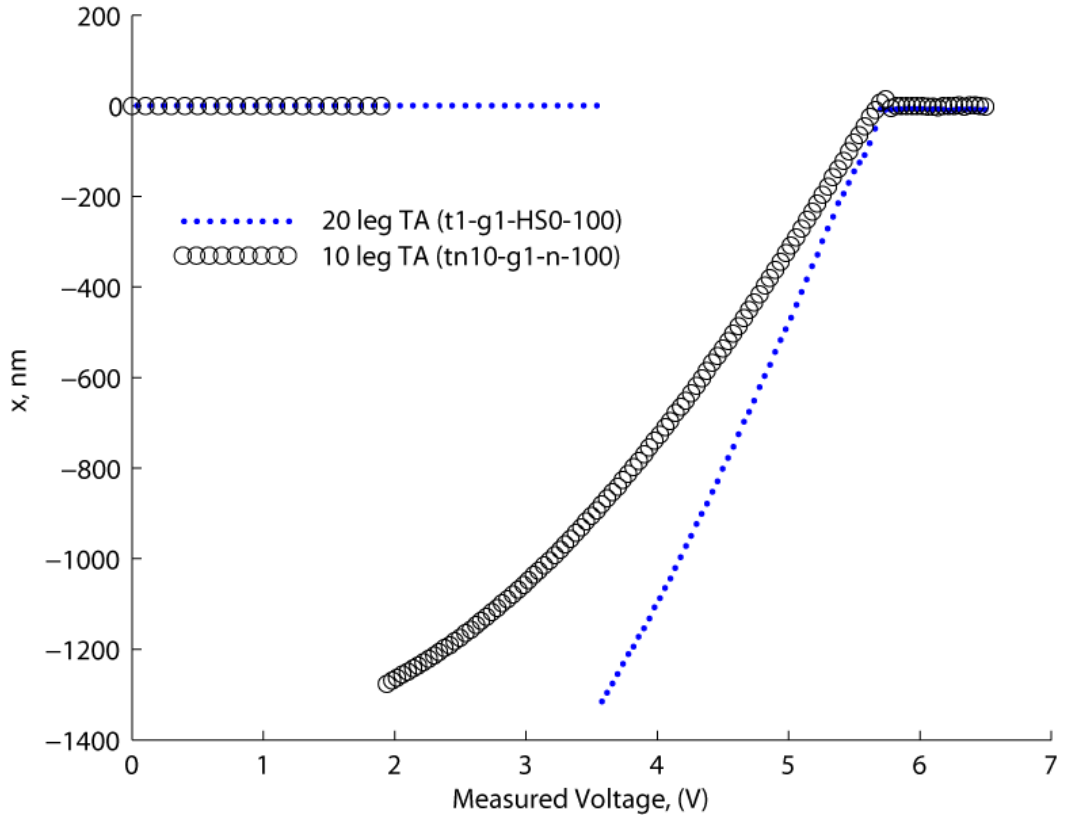
Example Data



The T-bar breaks at the same displacement independent of the number of legs (validation)

Direct fracture strain measurement. Need E but not cross-sectional area to know strength

σ_f=164*(1.3/70) GPa
= 3 GPa

Implies no strong dependence on temperature

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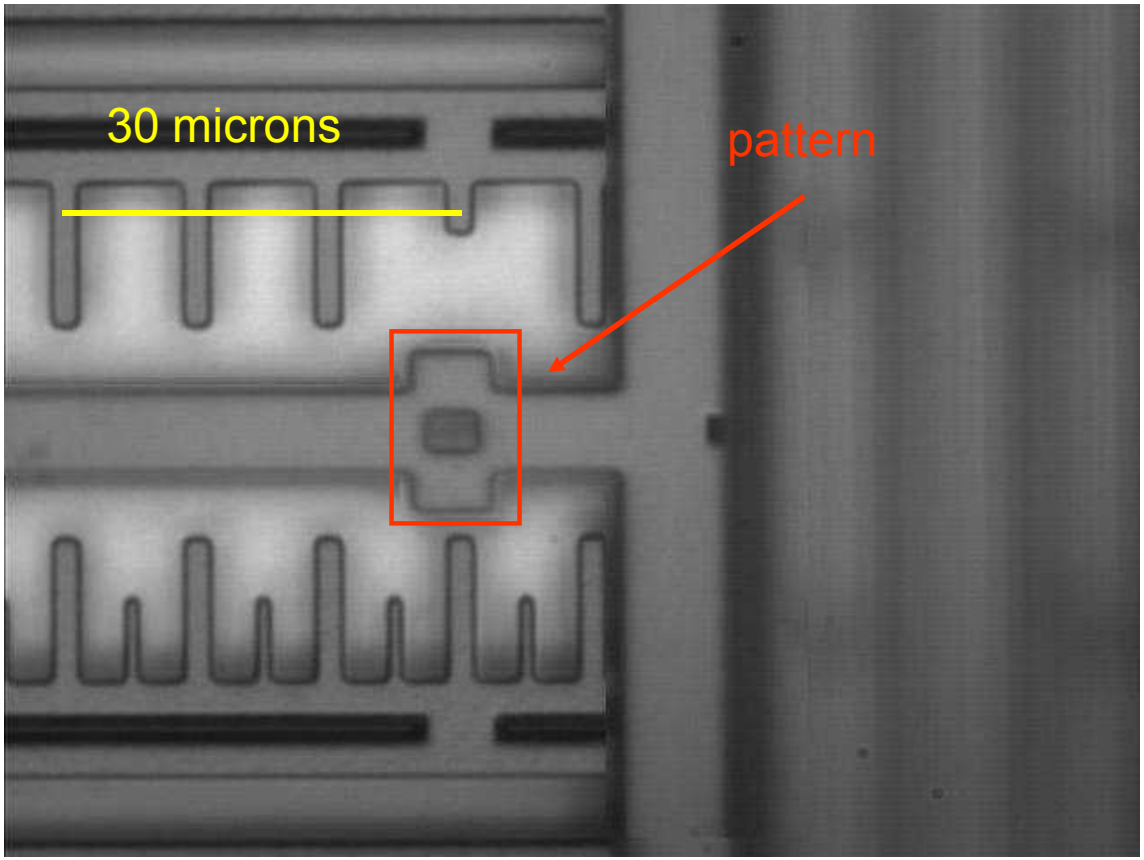
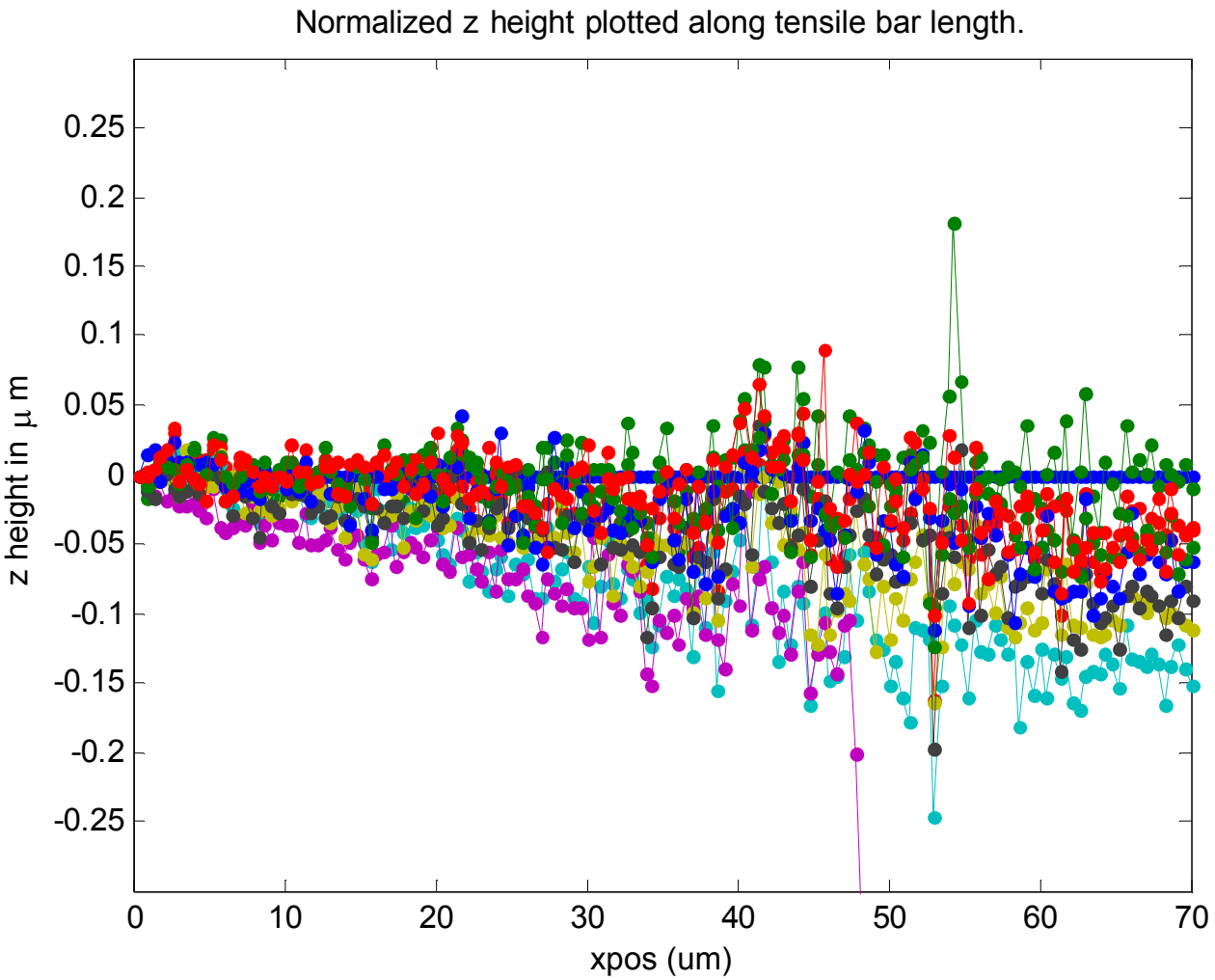
Optical Metrology – Pattern matching



Sub-pixel pattern matching using a 50X mitutoyo objective yields ±10 nm resolution

Out-of-plane alignment better than 0.2°



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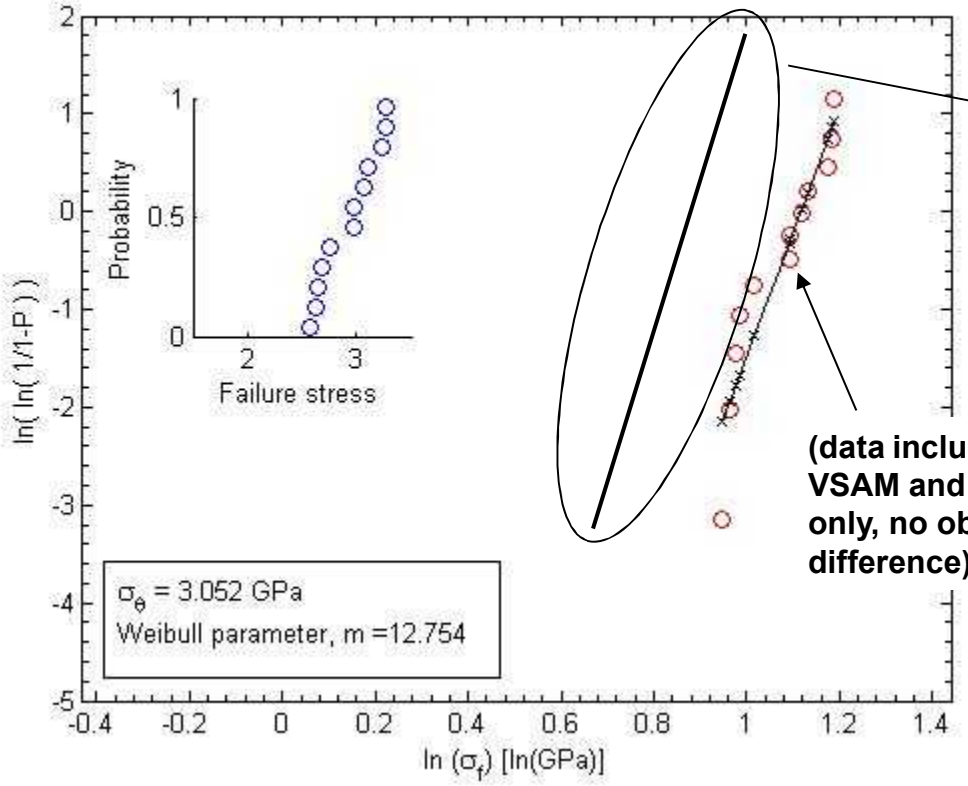
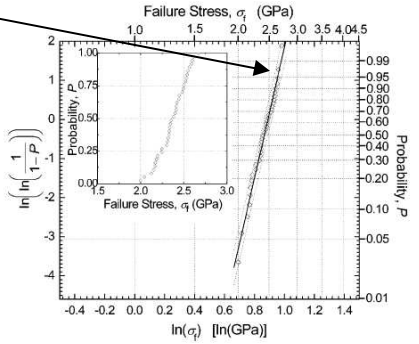
Weibull plot of 12 measurements



(data includes VSAM and CPD only, no obvious difference)

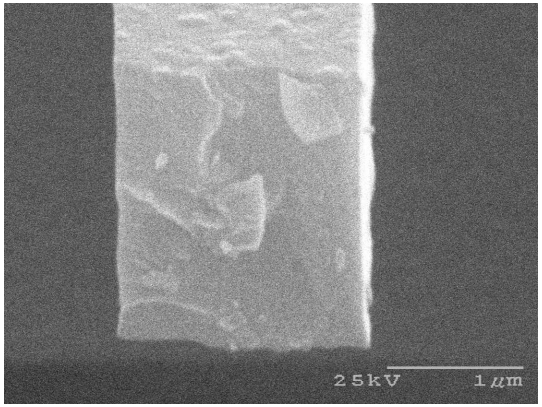
Boyce (JMEMS, 2007)



g. 3. The failure probability (inset) and Weibull transform observed for a imodal strength distribution of the 150 μm long poly3 tensile structures.

σ_θ= 2.43 GPa
m=16.7

Fracture surface



Possibly σ_θ higher because:

1) we have a direct strain measurement (would expect (2/1.7)2.43=2.86 GPa for Boyce data)

2) lot-to-lot dependence

S. S. Hazra. M. S. Baker, J. L. Beuth & M. P. de Boer, J. Micromech & MicroEng (2009)

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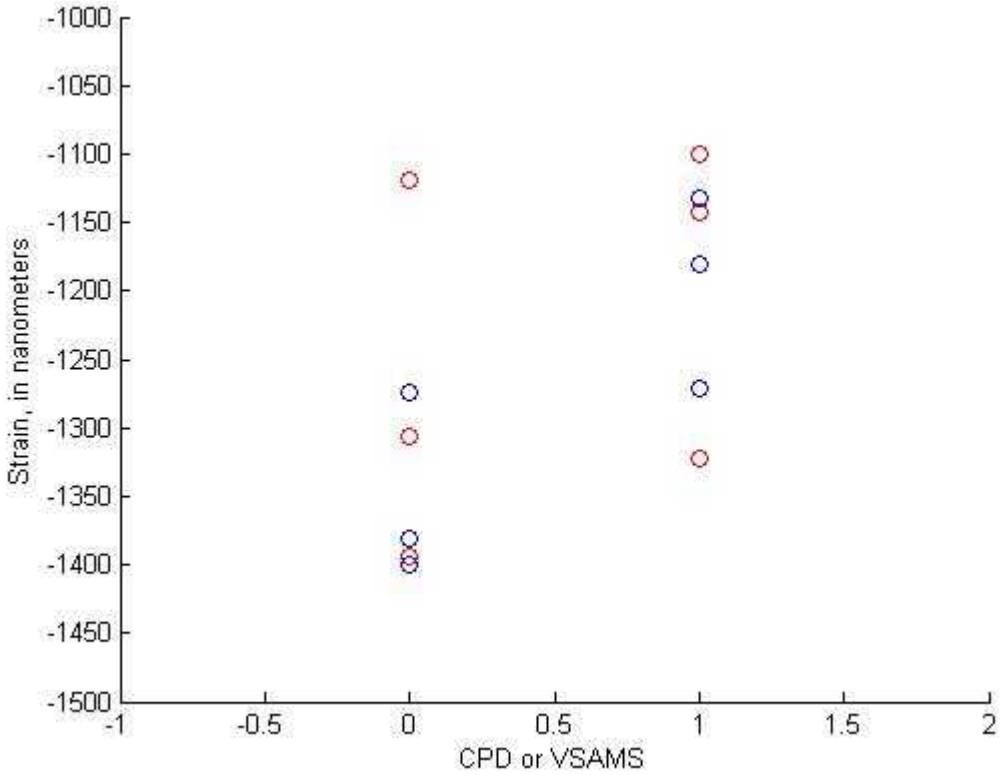
CPD vs SAMS – no apparent effect



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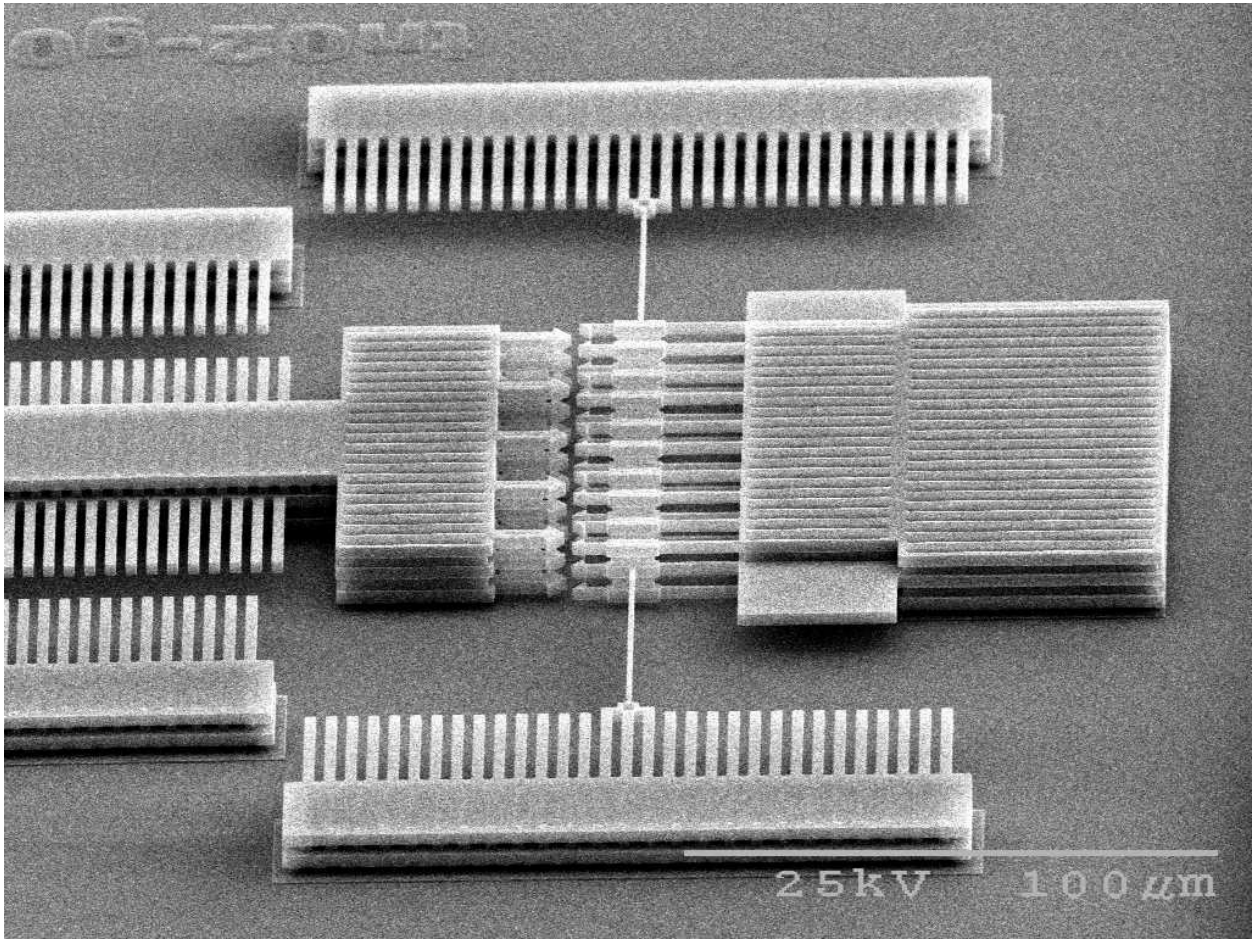
Design with grips only (no tensile bar)



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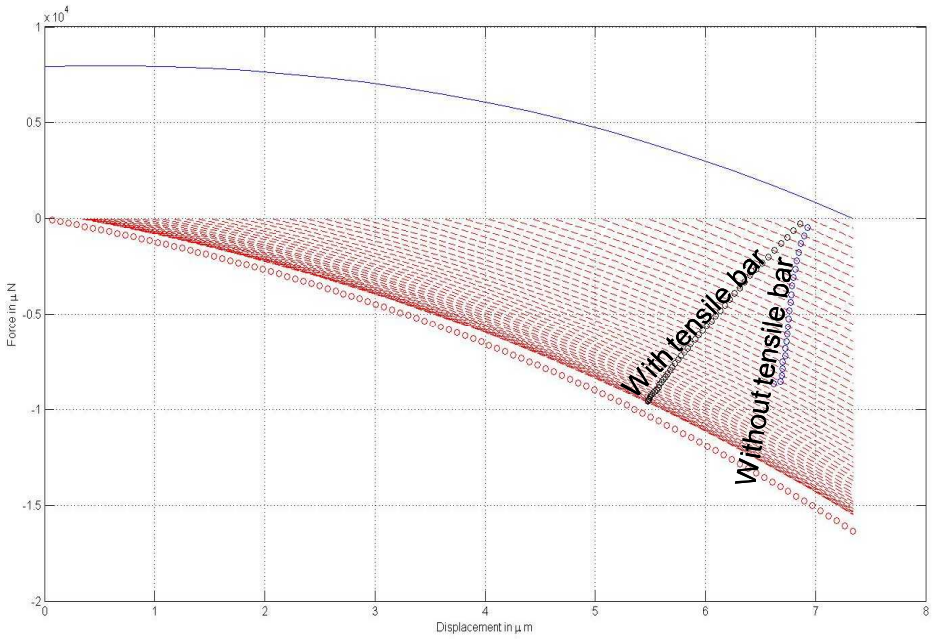
Using combined modeling and measurement approach, we can estimate gripper and T-bar compliances and hence breaking forces



Stiffness

Grips:
36627 N/m (modeled)
40000 N/m (measured)

Grips & T-bar
8987 N/m (modeled)
6818 N/m (measured)

- Red dashed lines are the structural forces at specific voltages
- Can observe “settling in” of grips only
- Measured versus estimated compliances agree relatively well! Inspires confidence in models…
- Shows that the grippers failed at lower loads for no tensile bar designs. How can this be?
- Reflects the ambiguity in defining gripper fracture (only one pair breaks which allows the rest to slip through from unbalanced forces)

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Testing of brittle specimens

- **Want to develop high forces over small displacements, but keep near room temperature**
- **The device concept works. Alignment is very good.**
- **The experiment directly measures fracture strain and fracture stress for a linear-elastic material.**
- **Round-robin test with Brad Boyce's pull-tab method is planned.**

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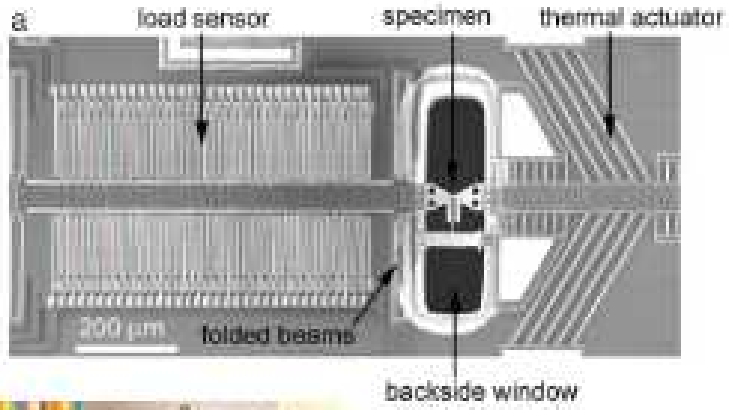
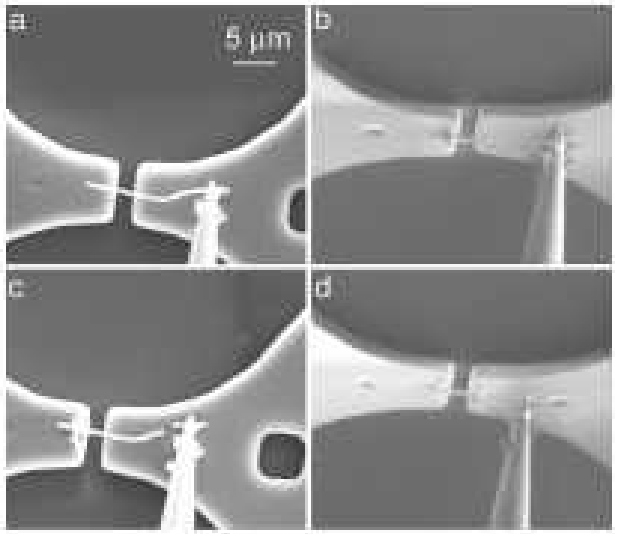
Nanofiber testing

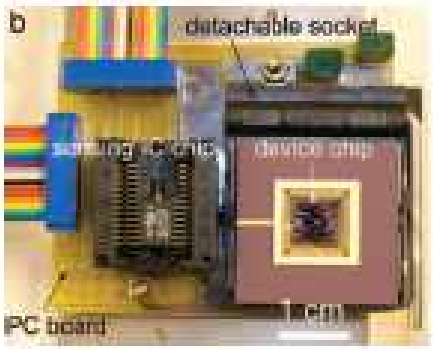
An electromechanical material testing system for *in situ* electron microscopy and applications

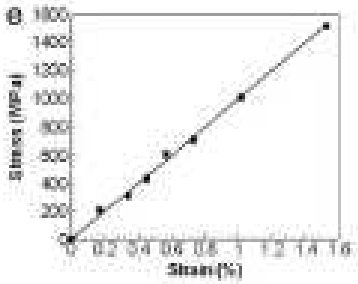
Yong Zhu and Horacio D. Espinosa*

Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208









Zhu & Espinosa (PNAS 2005)

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ductile fiber testing

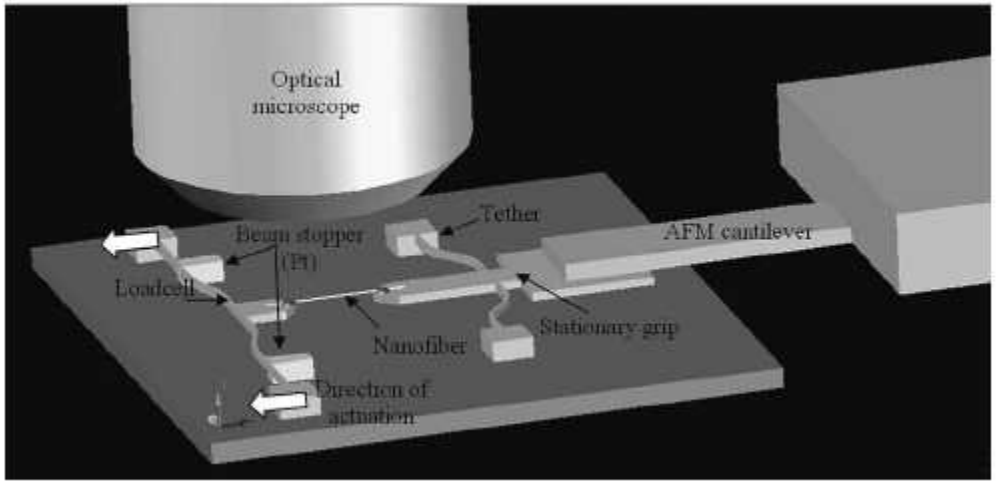
REVIEW OF SCIENTIFIC INSTRUMENTS 78, 085108 (2007)

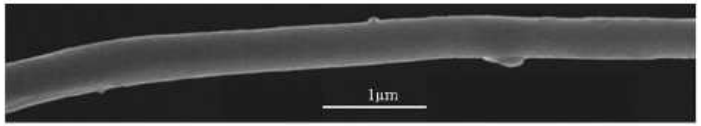
Novel method for mechanical characterization of polymeric nanofibers

Mohammad Naraghi and Ioannis Chasiotis
Aerospace Engineering, University of Illinois at Urbana Champaign, 325 Talbot Lab, 104 S. Wright Street, Urbana, Illinois 61801

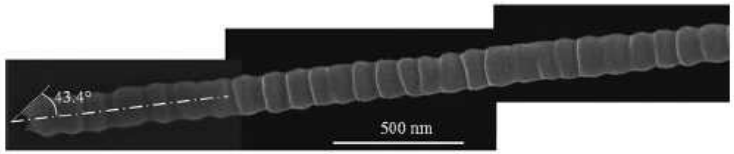
Harold Kahn
Department of Materials Science and Engineering, Case Western Reserve University, Cleveland, Ohio 44106-7204

Yongkui Wen and Yuris Dzenis
Department of Engineering Mechanics, University of Nebraska, Lincoln, Nebraska 68588

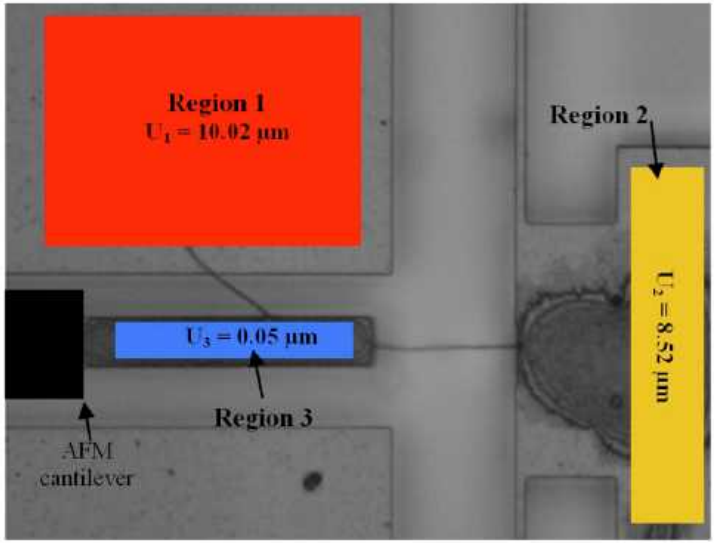


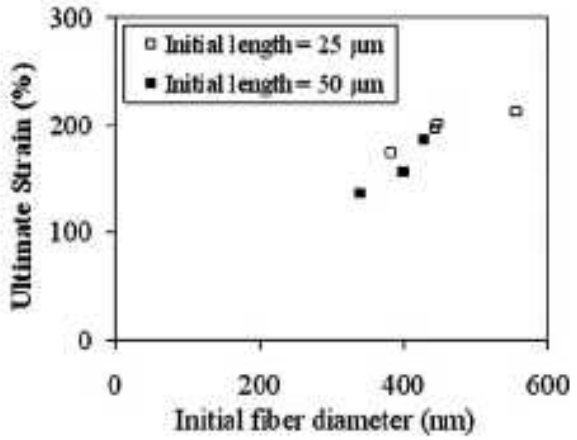


(a)



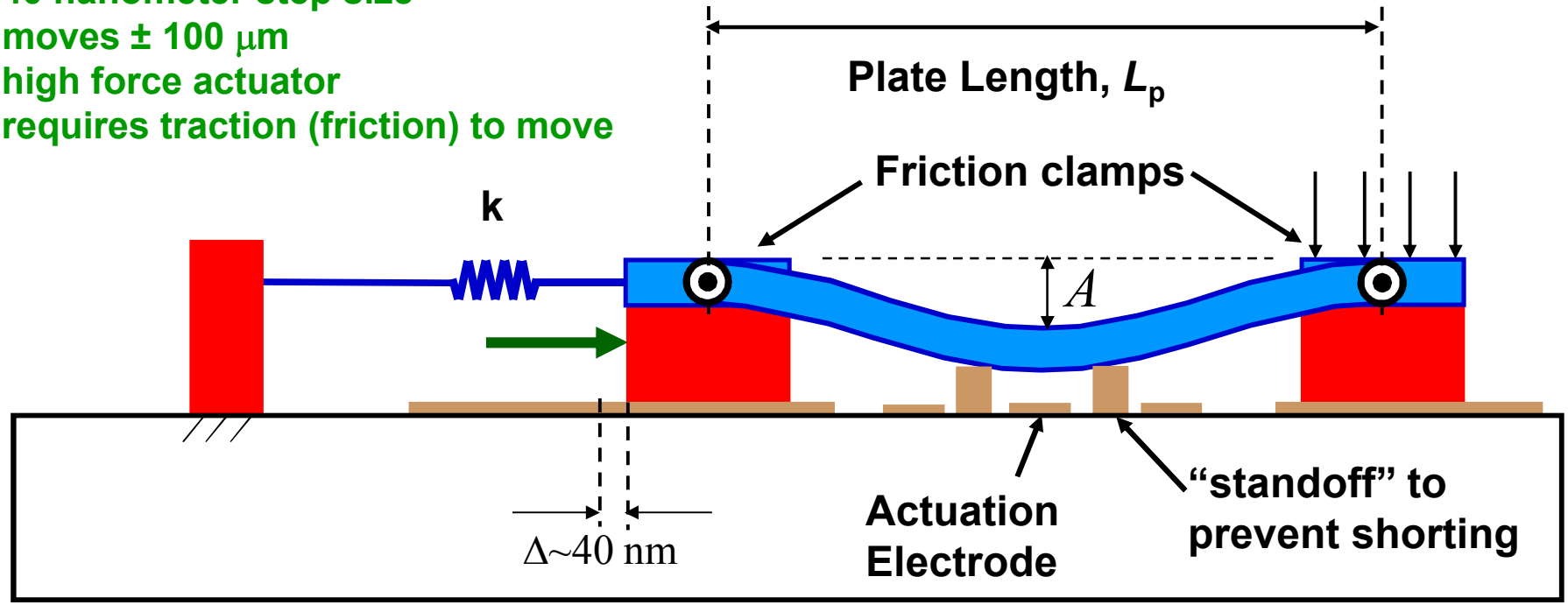
(b)





ductile fiber testing – propose nanotractor for on-chip actuation

- 40 nanometer step size
- moves ± 100 μm
- high force actuator
- requires traction (friction) to move



$$F_{\max} \sim 2Ewt\left(\frac{A}{L_p}\right)^2 \approx 1\,\text{mN}$$

large tangential force range

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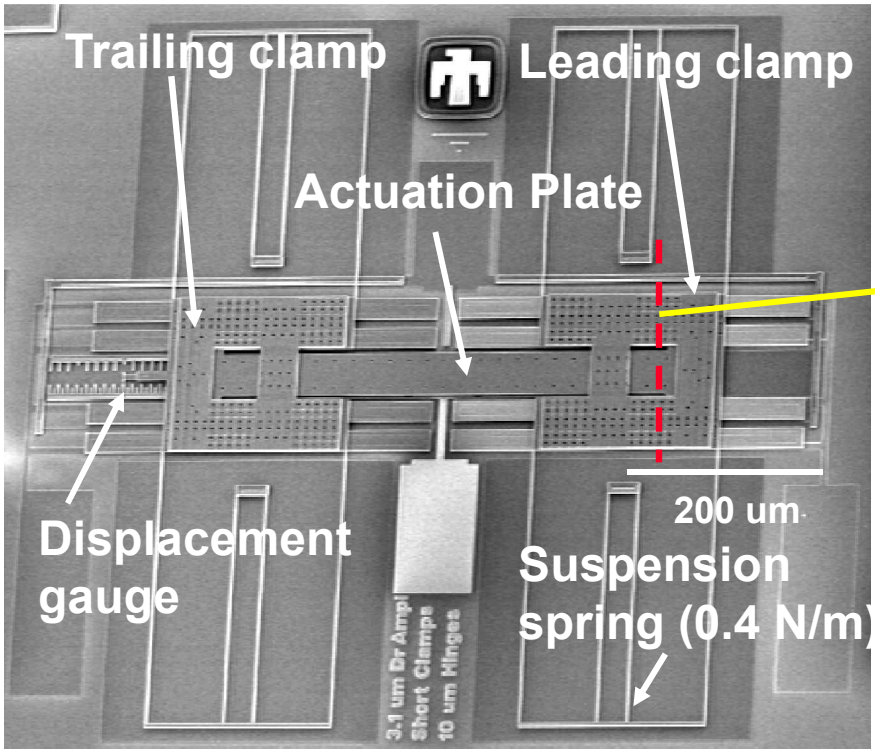
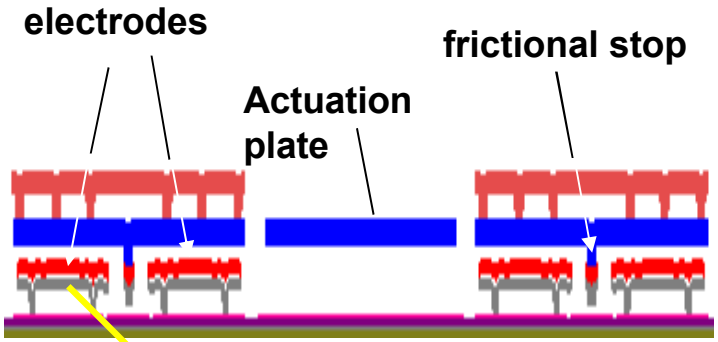
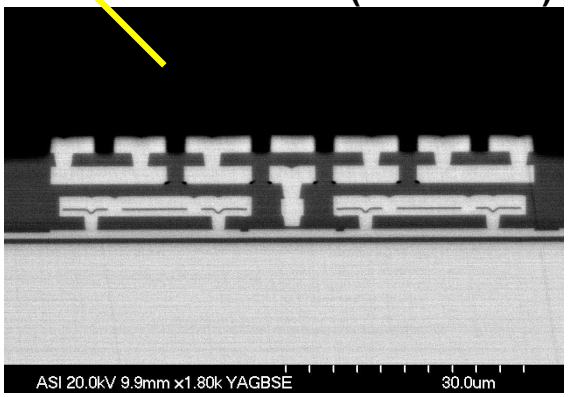
Nanotractor implementation





Cross-section(schematic)



SEM of Friction Clamp

High-performance surface-micromachined inchworm actuator, de Boer, MP; Luck, DL; Ashurst, WR; Maboudian, R; Corwin, AD; Walraven, JA; Redmond, JM: Journal of Microelectromechanical Systems; Feb. 2004; vol.13, no.1, p.63-74

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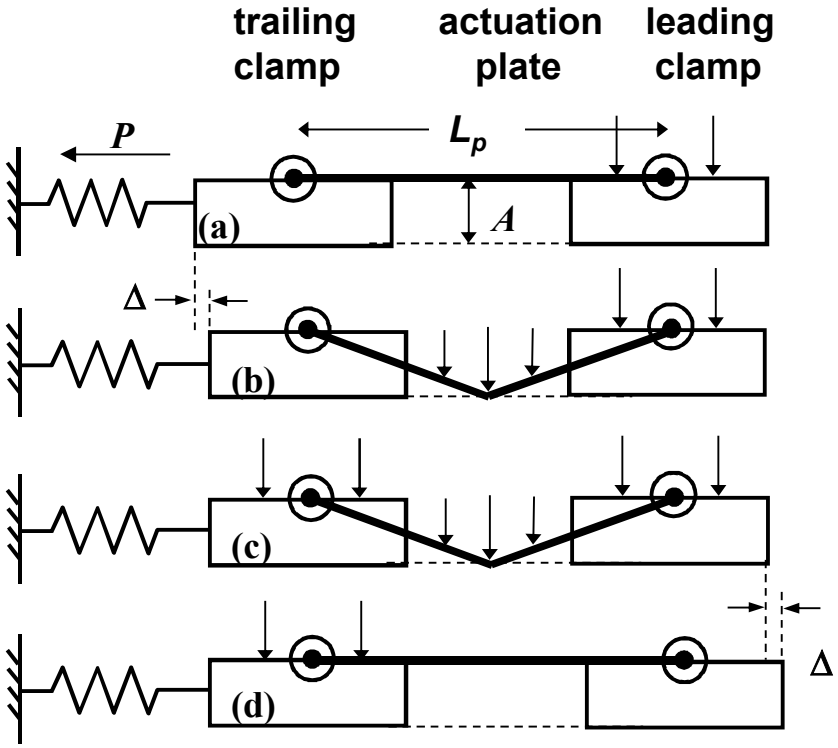
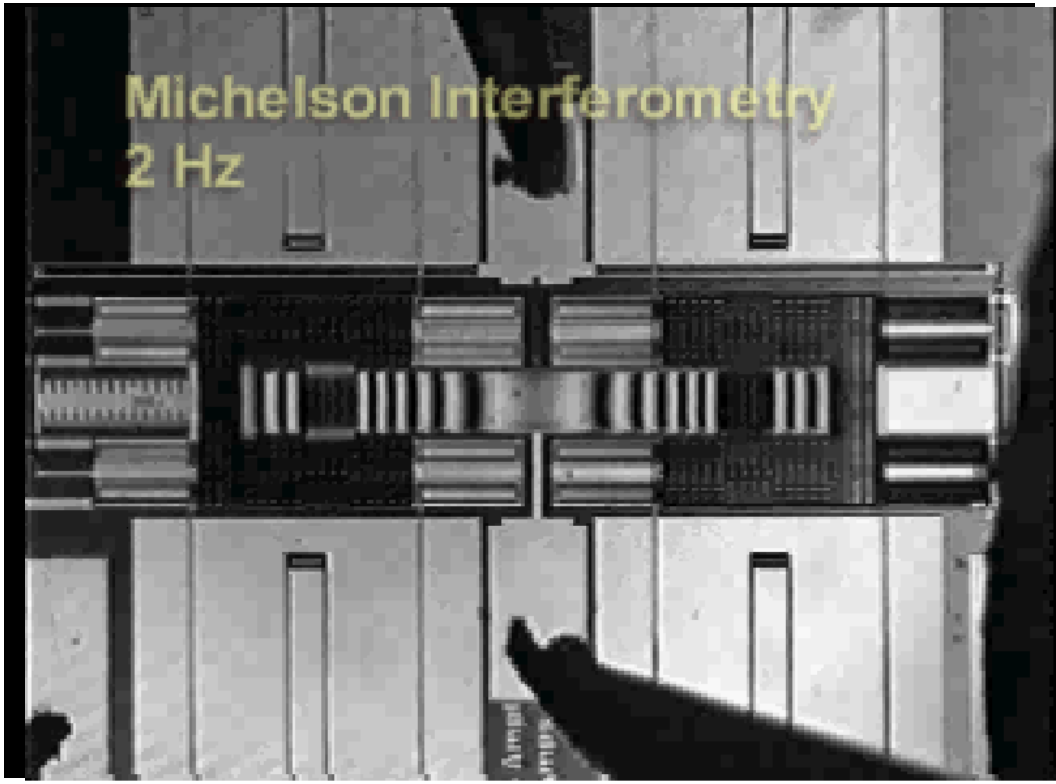
Driving the Nanotractor





- (a) Clamp RHS
- (b) Pull down driver beam
- (c) Clamp LHS
- (d) Relax RHS & driver beam

Operates up to 5 mm/s

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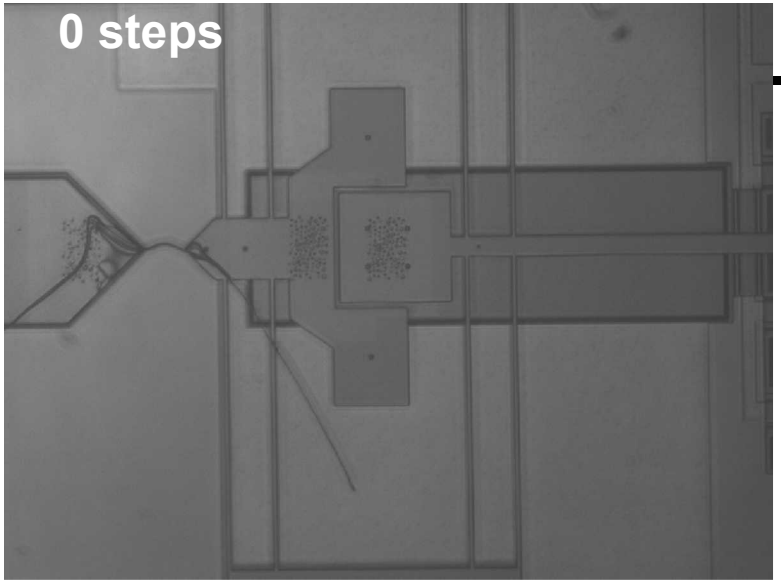
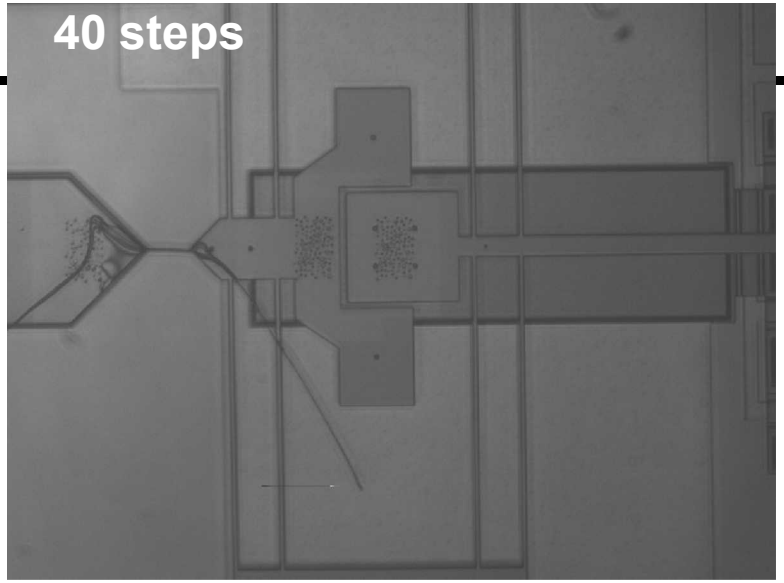
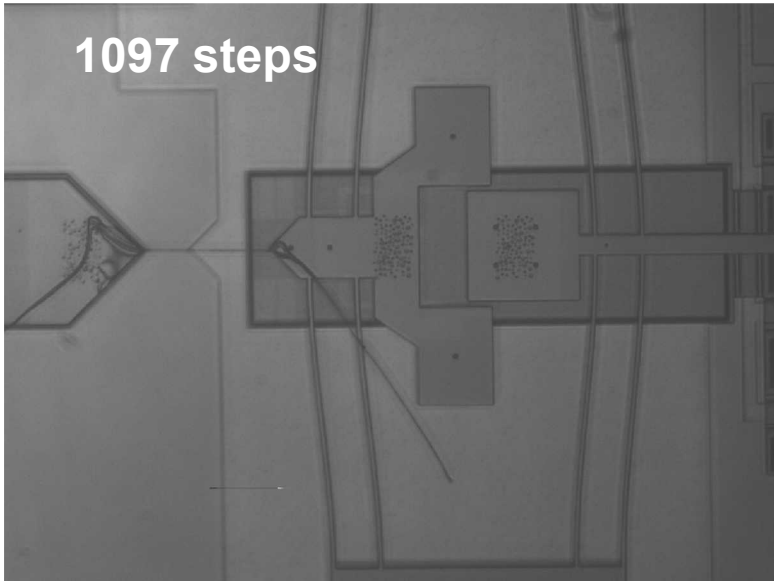
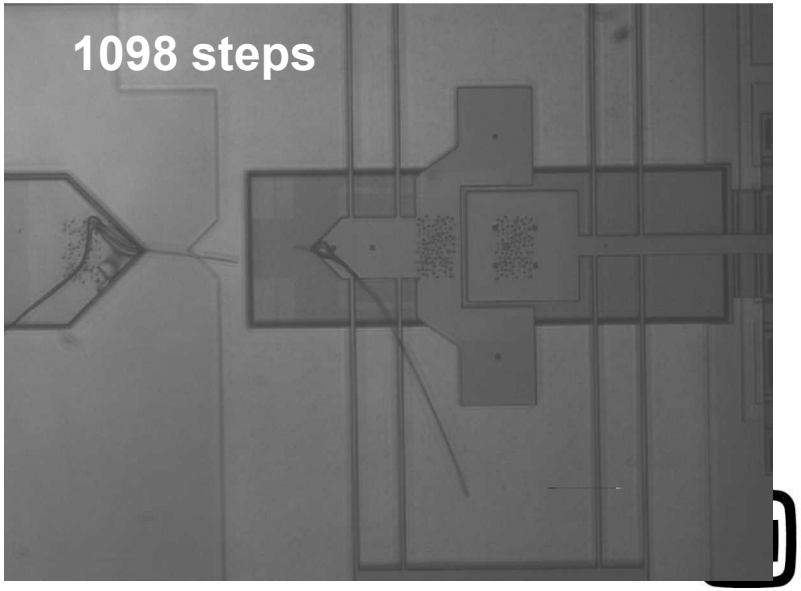
Chip_07_29_2009_01

Test demonstration









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Ductile fibers

- **Want to develop high forces over large displacement range**
- **Need only to align fiber to load spring**
- **Proof-of-concept shown**
- **Quantification possible**

Closing Thoughts

In-situ nanomechanical testing:

- **Samples can be adjacent to real devices**
- **More work to make the specimens, *but***
  easier to test samples and
  to perform a wide range of tests

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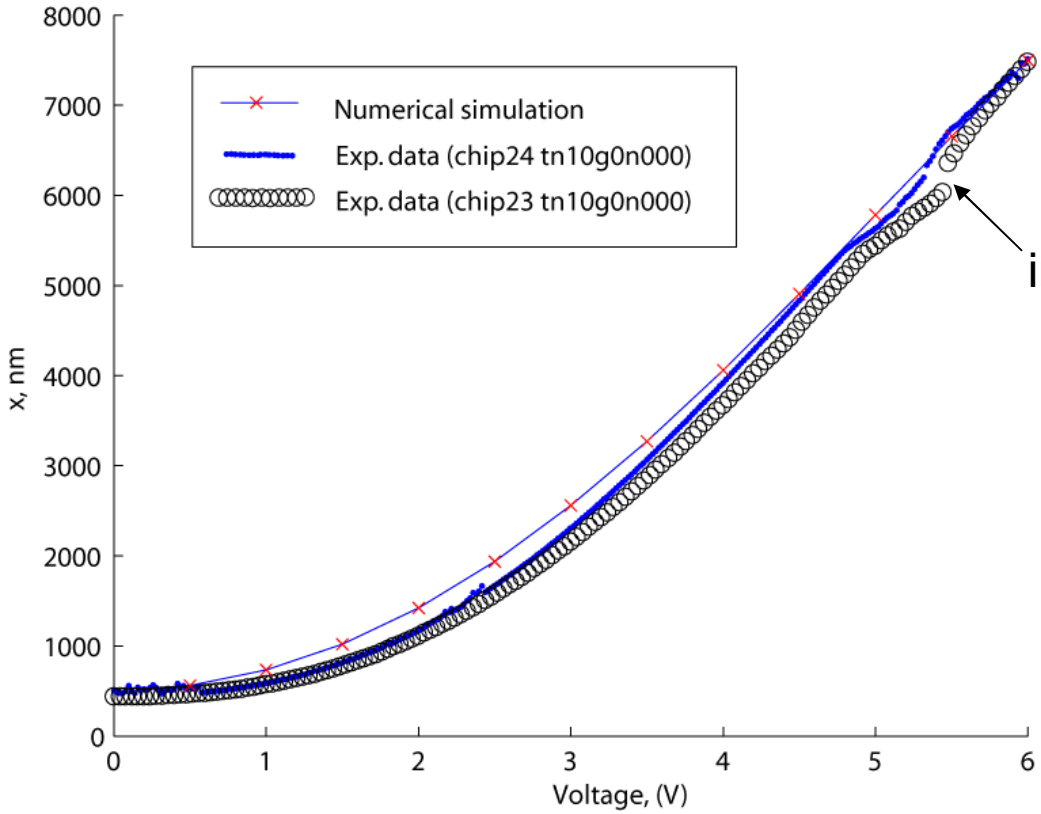
The unloaded displacement model versus measured values agree fairly well



lower breaking force of grips only is probably not due to model error.

insertion

- Simulation and experimental data for insertion stage.
- Initial displacement (x @ V=0) is from residual stress of 10 MPa (compressive).

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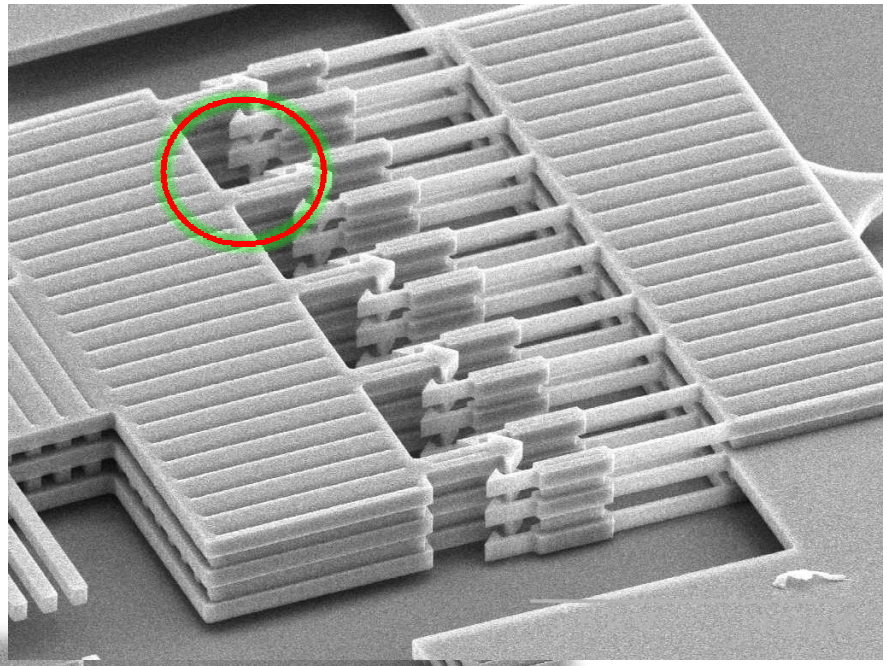
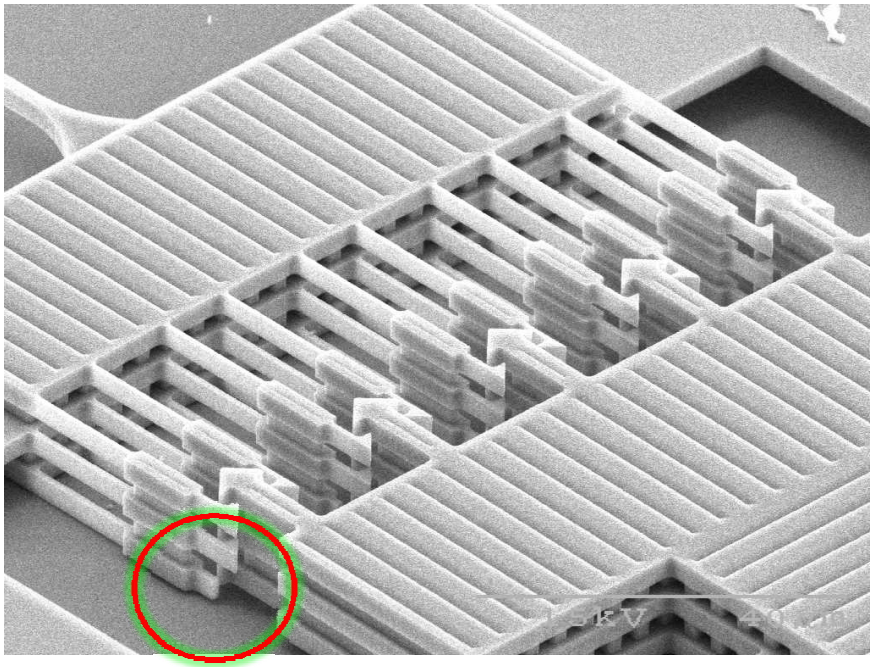
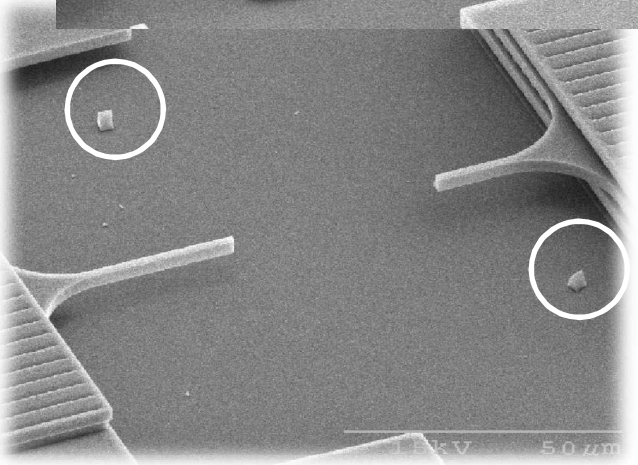
If the grips survive the fracture, then the results are unambiguous, but they don't… chicken or egg problem!!







- Location of suspect broken female grips shown in red circles
- Mode of failure unknown
- Did it break before tensile specimen failed or after?
- Did it break from the normal+bending loads on the female grips or from a collision w/ ground?

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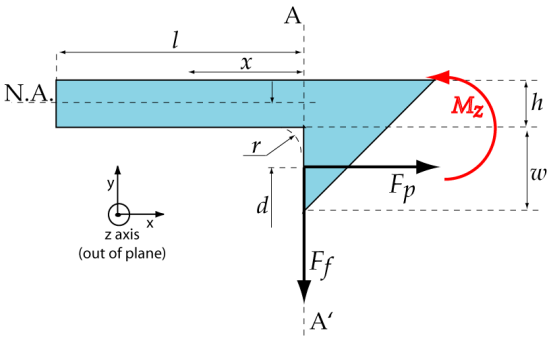
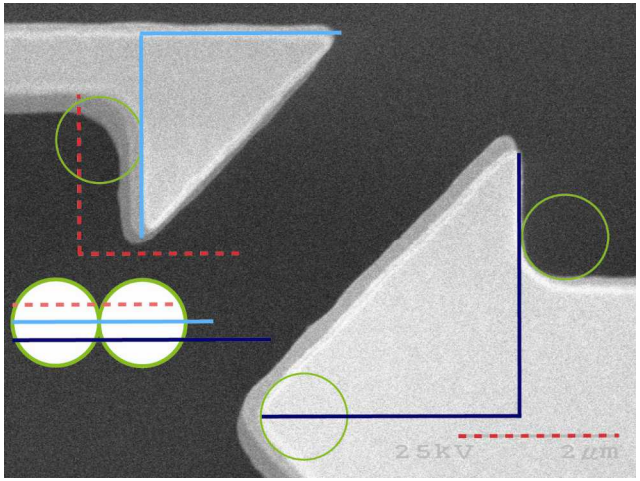
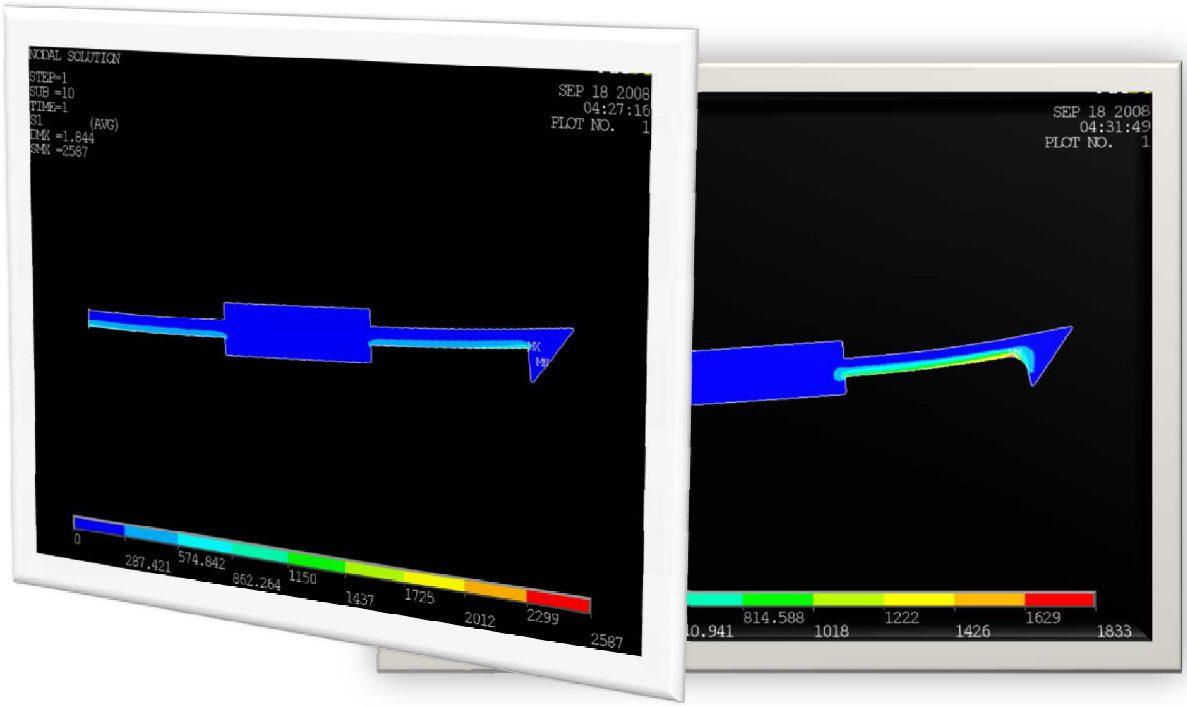
We are working to estimate the gripper stresses and to redesign the gripper geometry to be more robust



•Net moment from off -centered load causes bending.

•Stress concentrated due to geom. discontinuity.





•Process induces a curvature of 0.5 μm. Max principal stress =3 GPa

•We examine a deliberate curv. of 1μm along with a thicker x-section; Max principal stress = 1.8 GPa (upper estimate)

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I. Device idea and design

II. Experimental Results

III. Future Work

IV. Your feedback?

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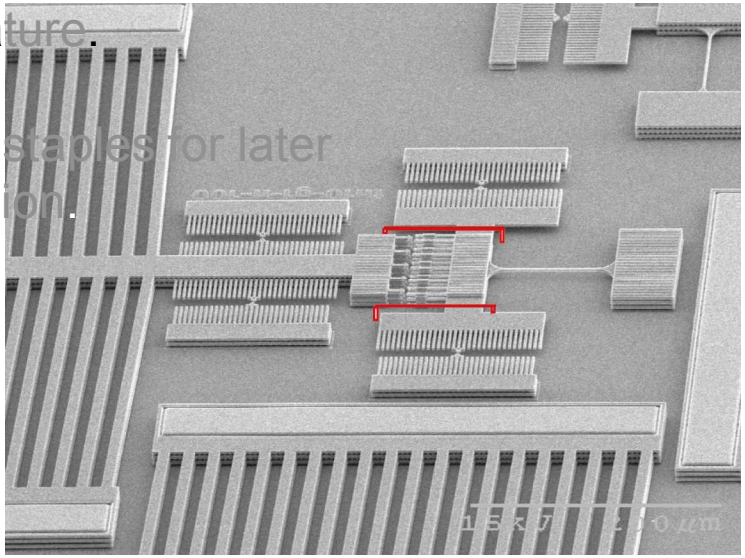
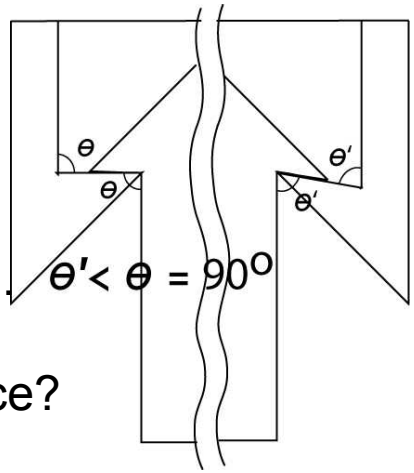
Layout variations

S.N.	TA	Grip	Mod.	Mod. val.	Heatsink	TB Length	maxDisp	Input I	Output F	Temp
1	t1MnumL	g1	numLegs	10	n	100	8.4119	177.6	12.302	603.4
2	t1MnumL	g1	numLegs	15	y	100	8.3798	266.2	16.028	600.5
3	t1MnumL	g1	numLegs	20	y	100	8.3878	355	19.068	601.3
4	t1MnumL	g1	numLegs	30 (250 w)	y	30	8.3482	532	37.042	597.78
5	t1MnumL	g1	numLegs	40	y	30	8.3878	710	45.341	601.2
6	t1Moff	g1	offset	15	y	100	6.4827	355	19.909	602.1
7	t1Moff	g1	offset	17	y	100	6.061	355	19.943	602.44
8	t1Moff	g1	offset	20	y	100	5.5086	355	19.822	603.02
9	t1	g1MnumG	numGrips	3	y	100	8.3878	355	18.958	601.3
10	t1	g1MnumG	numGrips	7	y	100	8.3878	355	19.116	601.3
11	t1	g1MnumG	numGrips/	11	y	100	8.3878	355	19.159	601.3
12	t1	g1Mthet	GD/theta	30 deg.s	y	100	8.3878	355	19.068	601.3
13	t1	g1Mthet	GD/theta	60 deg.s	y	100	8.3878	355	19.068	601.3
14	t1	g1Msxc	GD/sacOxcut	further from grip	y	100	8.3878	355	19.068	601.3
15	t1	g1Msxc	GD/sacOxcut	No sxcuts on GD	y	100	8.3878	355	19.068	601.3
16	t1	g1	Heat sink	0 (Absent)	n	100	8.3878	355	19.068	601.3
17	t1	g1	Heat sink	Small	n	100	8.3878	355	19.068	601.3
18	t1MnumL	g1	numLegs	20	y	100	8.3878	355	19.068	601.3
19	t1MnumL	g1	numLegs	20	y	100	8.3878	355	19.068	601.3
20	t1MnumL	g0	numLegs/No TB.	10	n	0	8.4119	177.6	17.994	603.4
21	t1MnumL	g0	numLegs/No TB.	2	n	0	8.3878	35.5	3.493	601.3

1. Reduce stress concentrations on the gripper x-faces using locally thicker cross-sections and greater rad. of curvature.
2. Prevent the broken bits from flying off by using staples for later examination. Staples also prevent in-plane torsion.
3. Reduce the baseline no. of TA legs.
4. Poly2 and Poly4 tensile specimens.
5. Heat sinks with holes.
6. Length of tensile specimens.
7. Increase bond pad area.
8. Changing f-gripper x-face angle for better locking.
9. A push-device in addition to the current pull-device?





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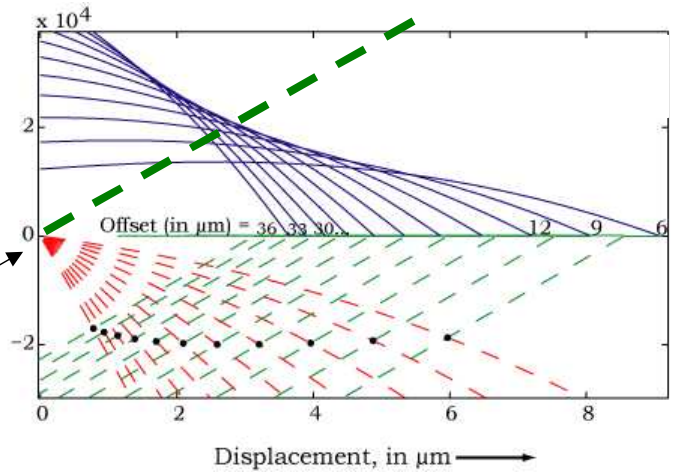
Use TA in push mode without grippers?



Loading curve for a device where fracture occurs upon pushing (heating) – TA max force about the same!

Advantage:
No grips

Disadvantages:
Fracture occurs when TA is at max temperature
Need to account for residual stress (less absolute precision)

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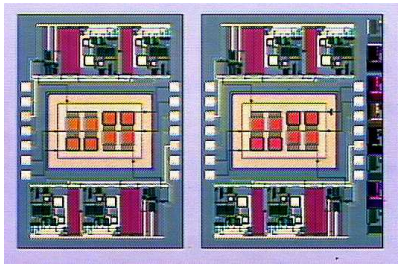
- **Gripper design analysis including insertion and frictional characteristics**
- **Experimental data from ~1000 devices**
- **Comparison to existing results and methods (Boyce et al., JMEMS 2007)**
- **Modeling effect of conducted heat from thermal actuator on tensile specimen and exp. results**
- **Calibration of displacement metrology**
- **Fatigue studies possible with this configuration**

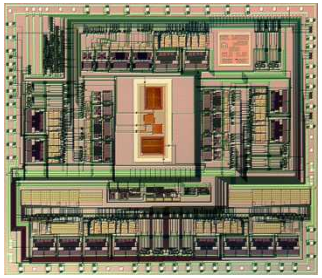
MEMS are RELIABLE – Industry chooses simpler devices

Class I
No Moving parts



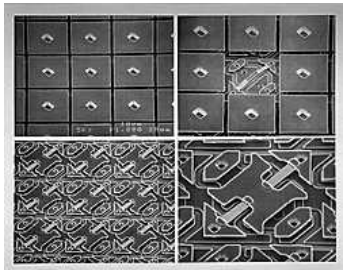
Accelerometers
Pressure Sensors
Inkjet Print Heads
Strain Gauge

Class II
Moving Parts, No Rubbing or Impacting Surfaces



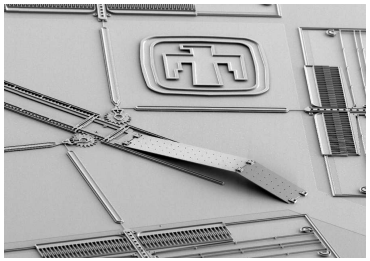
Gyros
Comb Drives
Resonators
Filters

Class III
Moving Parts, Impacting Surfaces



TI DMD ($ 1B)
Relays
Valves
Pumps
Optical Switches

Class IV
Moving Parts, Impacting and Rubbing Surfaces



Optical Switches
Shutters
Scanners
Locks
Discriminators

Billions of inkjet print cartridges produced using HP technology!
Analog Devices ships 1 million MEMS accelerometers a week!
Texas Instruments has shipped over 2 million DLP subsystems!

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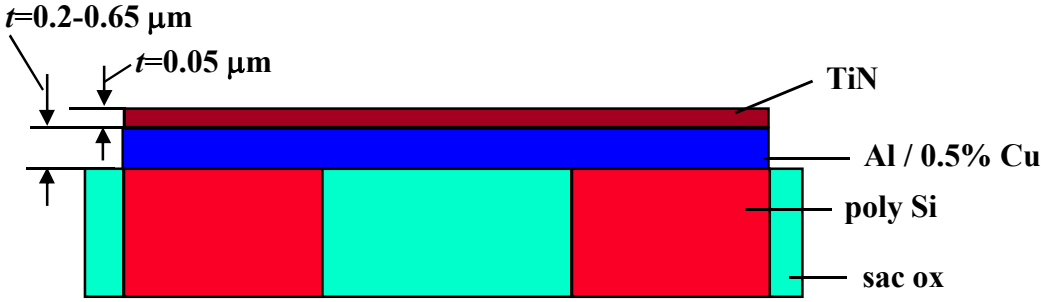
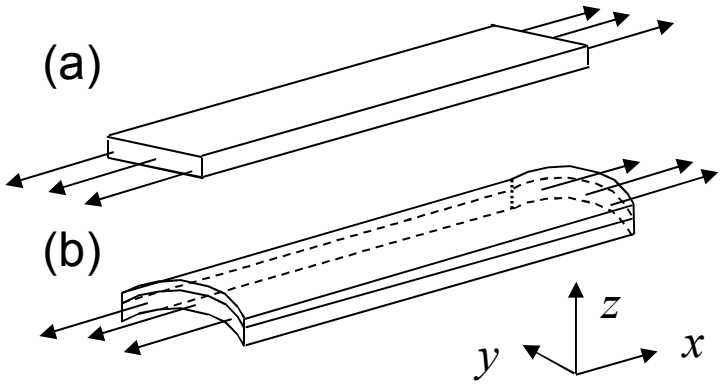
Sample fabrication, revisited

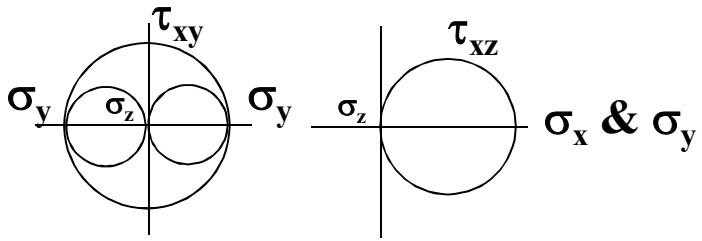




ff beam interferogram

100 μm

(c) bottom top (at interface)



Compressive TiN protective layer induces mechanical stress relief during release

(TiN is removed after release etch)

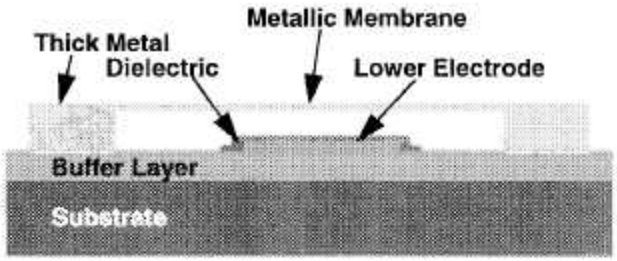


Fig. 1. Cross section of an RF MEMS capacitive switch.

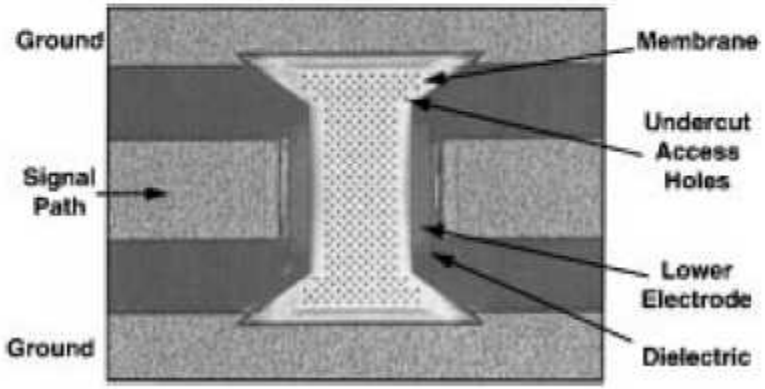
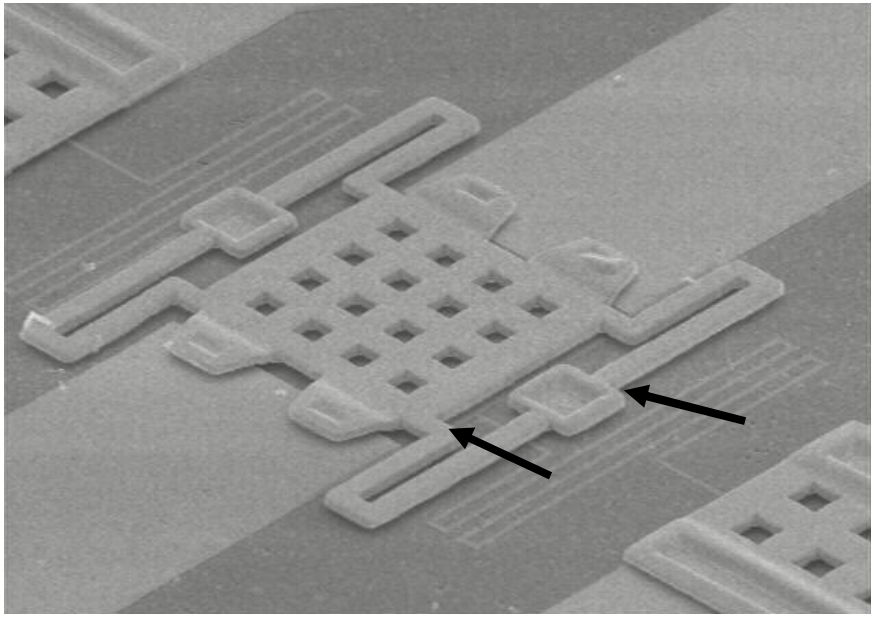


Fig. 2. Top view of a shunt MEMS capacitive switch.



IEEE MICROWAVE AND GUIDED WAVE LETTERS, VOL. 8, NO. 8, AUGUST 1998

Performance of Low-Loss RF MEMS Capacitive Switches

Charles L. Goldsmith, *Senior Member, IEEE,* Zhimin Yao, *Member, IEEE,*
Susan Eshelman, *Member, IEEE,* and David Denniston, *Member, IEEE*

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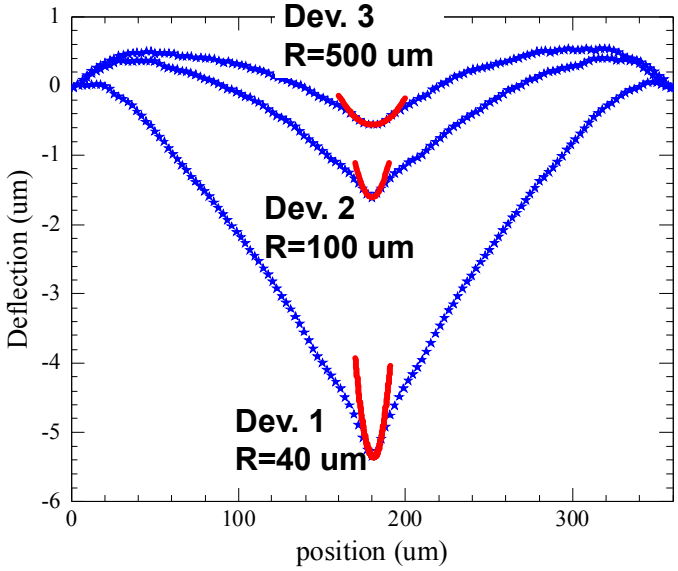
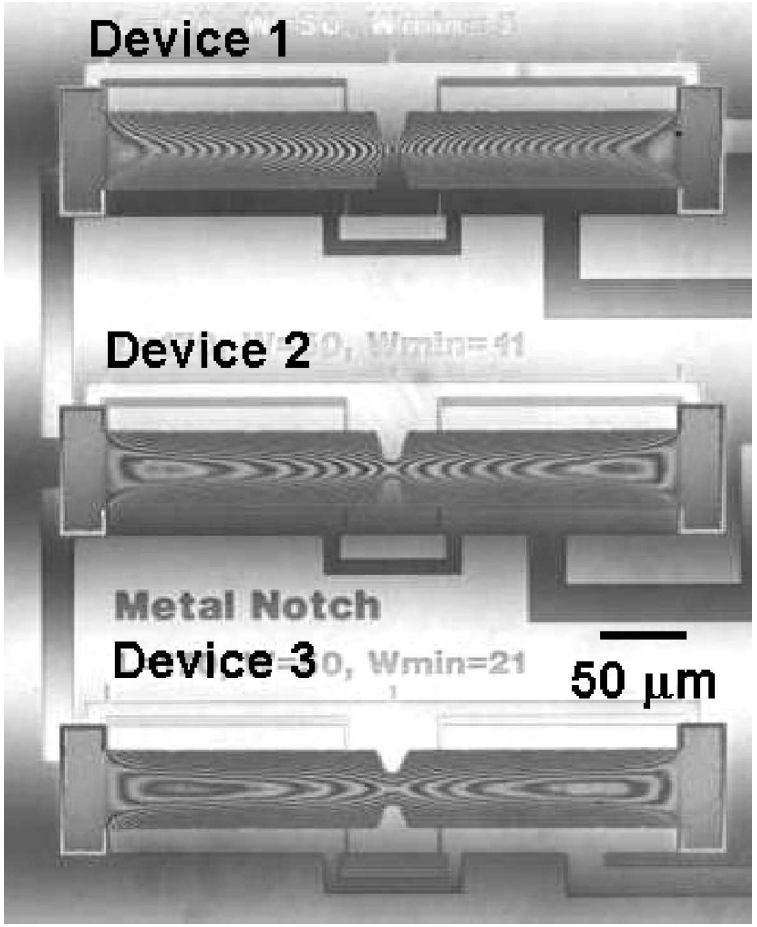
TiN also induces arc lengthening in the notched devices, stretching the gage section in Devices 1& 2





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Assess the Young's Modulus with a cantilever geometry

Paradigm for study of properties in MEMS

Assess the needs

Design & Model Test Structures

Fabricate

Test

Analyze and compare to model

Look at course outline to see what can be incorporated

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